Provenance and Porosity analysis of the Greymouth Basin, New Zealand.

A thesis submitted in partial fulfilment of the requirements for the

Degree of

Master of Science in Geology

in the University of Canterbury

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University of Canterbury

2017

Frontispiece

View of 12 Mile Beach

"It is widely acknowledged that the high level of geological complexity inherent at Greymouth is considerably greater than that normally experienced in most producing coalfields elsewhere" (Bowman, Caffyn, Duff, 1984).

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Acknowledgements

First and foremost, I would like to thank my supervisor Dr Kari Bassett for lending her technical knowledge and expertise to this project, especially in the final months. I would also like to acknowledge the amount of time and effort she put into making sure the interruptions with the Geological Science Departments multiple moves of labs into temporary then new buildings and subsequent analysis issues, had as little impact as possible.

I would like to thank Dr Alex Nichols for stepping in to help with the geochemistry and supervising me while Kari was away. Other staff members include Rob Spiers, for his creation of thin sections while being considerably busy organising the move of the department and Chris Grimshaw, for the help and support with the thin section staining.

Thank you to the District of New Zealand North Youth Assistance Trust for the financial assistance in completing my research.

Thank you to my friends in the office for your help, you made every day fun and interesting even in the moments of panic.

Finally, I want to thank all my family for their constant encouragement and support. Specifically, to my parents, Kevin and Lynette for all the encouragement and financial support you provided over the years.

To Jade, thank you for the motivation and support throughout. You provided a reason to smile at the beginning and end of every day.

Abstract

The coal and lacustrine deposits of the Greymouth Basin have been explored for their economic potential. However, the associated coarse clastic sediments have not been as thoroughly investigated. Thus, there is continuing uncertainty about the provenance of the sediments and tectonic setting of the basin. This study uses conglomerate clast counts, sandstone point counts and geochemical analyses of clasts to examine the provenance of the Paparoa Group.

Results show a dramatic eastern vs western lithological difference with conglomerates primarily on the west side of the basin, sandstones on the east, and mudstones inter-fingering both. The clasts encountered were predominantly metasedimentary with granite, hornfels, and rare unusual volcanic clasts. Aplite was recorded in the lowermost conglomerates and faded out with the introduction of granitic clasts in the middle Paparoa Group. Trace element geochemistry on basaltic clasts in the basin shows a tholeiitic composition, a typical rift signature. Geochemistry analysis of the granites was inconsistent with either Rahu or Karamea Suite granites and best fits a new A-type granite, low barium (<5 to 80ppm) and Strontium (18 to 42 ppm), located somewhere offshore. The sandstone porosity was variable ranging from 1% to 37% with grainsize, location and stratigraphic position in the basin. The degree of weathering in the sandstones was also variable with feldspar alteration ranging from minor to major clays (5% to 30%).

Provenance and Geochemistry analysis show the sediment sources of the basin changed throughout time with results showing two main sources, an eastern granitic source, likely Buckland granite and the western Greenland Group metasedimentary sources. This contradicts some previous interpretations. Clast counts also show evidence for the un-roofing of a granitic source with the presence of aplite clasts lower in the basin conglomerates replaced by granite clasts stratigraphically higher. The volcanic clasts are evidence of active volcanism in the area which could be attributed to the rift setting. Porosity in the sandstones was variable with some good hydrocarbon reservoir potential. The lack of trap and cap rock in the Greymouth Basin being an issue. The Takutai Basin offshore contains similar sediments and

fulfils the lacking criteria making it a potential petroleum play. The Greymouth Basin can be used as an analogue for the lack of outcrop data in the Taranaki Basin.

Chapter 1 Introduction

1.1 Introduction

“The provenance of a sediment includes all aspects of the source area, including source rocks, climate, and relief” (Pettijohn, Potter, & Siever, 1972).

The term provenance comes from the Latin word ‘provenire’, meaning to come forth or to originate. However, in sedimentary petrology the term provenance encompasses all factors that refer to the production of sediment. These include the composition of the parent rock, physiography and climate or the source area from where the sediment was derived (Weltje & von Eynatten, 2004). The intent of sedimentary provenance investigations is to reconstruct and interpret the history of the sediment from the initial erosion from the parent or source rock to the final burial of detritus. However, the ultimate goal of provenance studies is to infer characteristics of the source area, from measurements of compositional and textural properties of sediments along with additional evidence from other sources (Pettijohn et al., 1972).

There is some controversy surrounding the sedimentary sources of the Late Cretaceous Greymouth Basin. There are two competing theories when it comes to the sediment sources. In 1952 Maxwell Gage first mapped and described the Paparoa Coal Measures in the Greymouth Basin (Figure 1.1). Gage believed there was a basement rock, Greenland Group source, in the east and a granitic source in the west. However, Newman (1985) and Ward (1997) thought the sources were the other way around, but no provenance investigations have been attempted to prove these theories. This thesis will use multiple sedimentary provenance analysis techniques to investigate the possible sources for the Paparoa Coal Measures. The provenance analysis will also help with determining a tectonic paleo-geographic model of the Greymouth Basin.

The Paparoa Coal Measures lie in the Greymouth Basin and contain large quantities of economically viable coal resources (Gage, 1952). Therefore, a majority of the research done into the Greymouth Basin has been focused on the coal. The Paparoa Coal Measures also contains a large amount of clastic sediments ranging from mudstone, sandstone, to boulder sized conglomerates. Previous studies into the Greymouth Basin have speculated, without a dedicated investigation, into the other lithologies. This is the equivalent of trying to complete a puzzle with a few missing pieces, close but not quite complete. All three different lithologies; mudstone, sandstone and conglomerate will be investigated with different sedimentary provenance techniques. This analysis will help fill in those missing pieces.

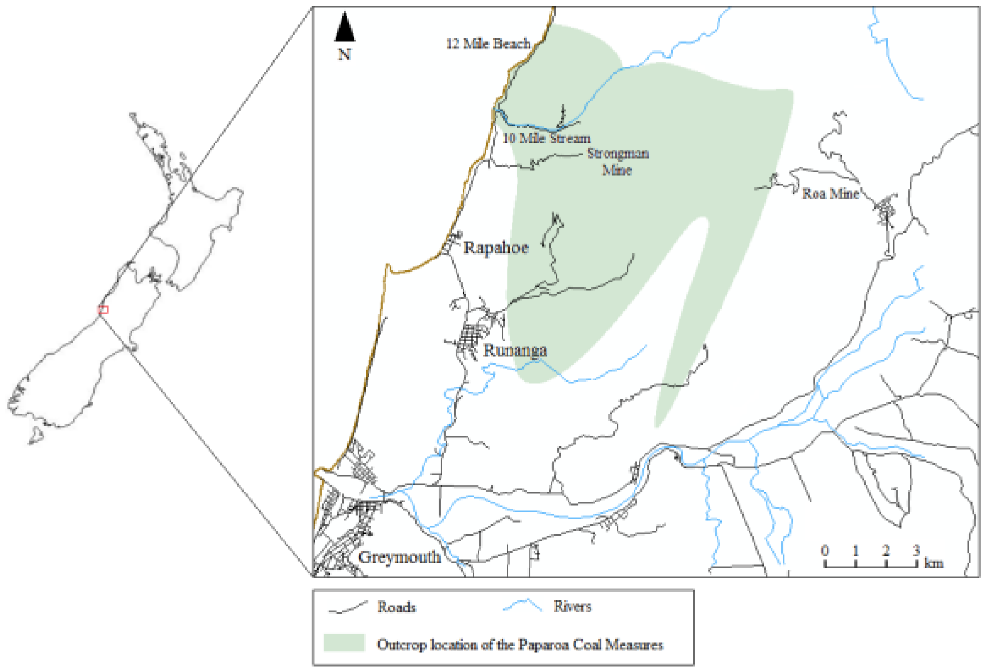

Figure 1.1 Location map of the Greymouth Basin and Paparoa Coal Measures extent and location (Cody, 2015).

The provenance analysis will also help to determine the tectonic setting as the composition of the sandstones can infer the tectonic setting. The relationship between sandstone compositions and tectonic setting, was recognized through the work of Dickinson & Suczek (1979), and Dickinson et al. (1983). They showed that by plotting the detrital framework categories of sandstone suites on a quartz, feldspar, lithics) (QFL) ternary diagram, resulted in information about the tectonic setting of the depositional basins and their associated provenance (Dickinson et al., 1983). The QFL diagram is divided into three main categories, with three sub-fields each, with the exception of the recycled orogen field. The three main fields are representative of three different types of tectonic regime, continental blocks, magmatic arcs, and recycled orogens (Dickinson et al., 1983). There is also a more specific QmFLt diagram which is similar to the QFL diagram, except that it plots exclusively monocrystalline quartz (Qm), and total polycrystalline lithics (Lt) (Dickinson et al., 1983). Dickinson and Suczek (1979) established that sandstone suites from different kinds of depositional basins, are a function of provenance types controlled by plate tectonics. In general, sediments derived from continental interiors and deposited within intracratonic basins, or along passive margins, are rich in detrital quartz, feldspar and poor in lithic fragments, especially volcanic lithics. Clastic sediment derived from recycled orogens is commonly more quartz and lithic rich than craton-derived sediment, even though the depositional setting on passive margins may be the same. Clastic sediments derived from volcanic arcs (continental or oceanic) are typically poor in detrital quartz and rich in volcanic lithics.

This study will use multiple provenance analysis techniques for the clastic sediments. Clast counts will be used to provide a statistical analysis of the constituents of the conglomerates (Johnsson & Basu, 1993). Point counts will be used to do the same with the components of the sandstones. This data will help provide evidence for determining the more dominant source of sediment for each formation, in the Paparoa Coal Measures and the tectonic setting. Geochemical analysis will be used to investigate the granitic clasts, mudstone, basalts and any volcanics to determine the major and minor trace elements within the clasts (Arribas, Critelli, & Johnsson, 2007). These results will help to trace back the source of the clasts and sediments. The combination of these analysis techniques will help recreate a paleo environment and tectonic model of the basin as it developed (Johnsson & Basu, 1993; Arribas et al., 2007).

Accompanying the main provenance research is an investigation into the porosity of the sandstones within the Paparoa Coal Measures, to look at the prospect of a possible reservoir rock. There is a documented history of multiple large natural oil seeps in the Greymouth Coalfield and region. These seeps have been around for a long time with drill holes investigating the surrounding area since the 1902 (Morgan, 1911; Nathan, Rattenbury, & Suggate, 2002). Subsequently there have also been multiple attempts with varying degrees of success at developing this into an economic resource. The sandstones of the Paparoa Coal Measures however, have not been investigated in reference to their potential as reservoir rocks, leaving a potential reservoir rock overlooked. Although this area has been under investigation for over a century no significant petroleum play has been found.

1.2 Geological History and Basin Formation

The break-up of Gondwana resulted in extension of the New Zealand continental crust during the Cretaceous to Paleocene approximately 105 - 55 Ma (Laird, 1994; Gaina, Müller, Roest, & Symonds, 1998; Laird & Bradshaw, 2004; Strogen, Seebeck, Nicol, & King, 2017). The eastern margin of Gondwana was dominated by a convergent plate boundary until 105 Ma, when the system abruptly changed to an extensional regime. The change in regime is thought to be a consequence of a failed subduction/collision of the Hikurangi Plateau, which allowed proto New Zealand to be captured by the western edge of the eastward moving Pacific Plate (Laird & Bradshaw, 2004). During this extension the Greymouth and Taranaki Basins were formed. The final result of the separation from Gondwana was a New Zealand continent that had been thinned and uplifted. There formed a series of well-developed fault bounded basins or grabens, surrounded by blocks of structurally higher basement in which the Greymouth Basin and Taranaki Basin were formed.

Two temporally distinct phases of rifting have been recognized in the region, and record the Gondwana break-up (Strogan et al., 2017). The first, mid-Cretaceous, rift phase (105 – 83 Ma), referred to as the Zealandia rift phase, caused the formation of the Paparoa Metamorphic Core Complex and is approximately parallel to the Tasman Sea and south-west Pacific spreading centres (Tulloch & Kimbrough, 1989; Schulte, Ring, Thomson, Glodny, & Carrad, 2014; Strogan et al., 2017). The second rift phase, of latest Cretaceous–Paleocene age (c. 80– 55 Ma), the West Coast Greymouth –Taranaki Basin rift phase, was mainly confined to a narrow strip in central Zealandia and trends approximately orthogonal to the Tasman Sea spreading centre (Strogan et al., 2017). These rift phases are separated by a period of uplift and erosion (83 – 80 Ma) synchronous with Gondwana break-up (Strogan et al., 2017).

The Paparoa Metemorphic Core Complex is just north of the Paparoa Basin and was developed during the first rifting system (Tulloch & Kimbrough, 1989; Schulte et al., 2014; Strogan et al., 2017). The Paparoa Metamorphic Core Complex developed in the Mid-Cretaceous due to continental extension conditioning the crust for the eventual breakup of the Gondwana Pacific Margin, which separated Australia and New Zealand (Tulloch & Kimbrough, 1989; Schulte et al., 2014). It has two detachment systems: the top north-east displacing Ohika Detachment at the northern end of the complex and the top south-west displacing Pike Detachment at the southern end of the complex (Tulloch & Kimbrough, 1989; Schulte et al., 2014). This caused core uplift which exposed considerable deformed lithologies in the area, including the Charleston Metamorphic Group (Kimbrough & Tulloch, 1989).

The Greymouth Basin was formed with the second stage of rifting associated with the spreading of the Tasman Sea, with an unknown amount of strike-slip component (Gage, 1952; Nathan, 1978; Newman, 1985; Ward, 1997). Rift basins are the result of stretching of the underlying lithosphere (Leeder, 1995). Lithospheric stretching is caused by one of two ways; first, passive rifting, where localised stresses arise along plate edge forces, and second, active rifting which involves upwelling of mantle melt and eruptive volcanics (Leeder 1995). Continental crust thinning, and stretching is a consequence of rift basins along with the formation of grabens and half grabens (Frisch, Meschede, & Blakey, 2011).

Grabens and half grabens are topographic lows, bounded by fault controlled slopes on one or both sides of the basin (Leeder & Gawthorpe, 1987; Gawthorpe & Leeder, 2000). Graben rift basins are symmetrical rift basins, with two dominant normal boundary faults accommodating the continental extension (Leeder & Gawthorpe, 1987). This results in steep topography and high energy depositional facies along both sides of the exposed footwalls, than in the centre of the basin (Leeder & Gawthorpe, 1987). The basin axis is dominated by moderate to low energy depositional facies (Leeder & Gawthorpe, 1987). Half graben rift basins are tectonically controlled by one dominant normal boundary fault, accommodating the tectonic extension (Leeder & Gawthorpe, 1987). This typically results in an asymmetrical basin, with a steeper faulted footwall margin that produces higher energy sediments, with moderate to low energy environments along the basin axis and the un-faulted hanging-wall hinge side. This directly impacts the location and type of depositional facies (Leeder & Gawthorpe, 1987). The relationship between subsidence, sediment fill and accommodation space creates very thick and extensive terrestrial sedimentary sequences of fluvial and lacustrine sediments, which often also contain coal and coaly source rocks (Kelts, 1988; Gawthorpe & Leeder, 2000; Allen & Allen, 1990; Connell, 2010).

1.3 Economic Geology

The West Coast of the South Island of New Zealand has been a geological economic source for around 150 years. The Greymouth Coalfield was discovered by Thomas Brunner in 1847 (Morgan, 1911) by the Grey River and mining in the area began about 20 years later (McNee, 1997). Multiple mining operations have been undertaken in and around the Greymouth Coalfield expanding to the north from the initial operation at Brunnerton.

There are three mine sites within the Greymouth Coalfield mining the coal, all of which are on standby due to the current coal prices. Spring Creek Mine, Strongman Mine at 9 Mile Creek, and Roa Mine in the east of the basin, all exploit the Paparoa Coal Measures.

Coal analysis within the Greymouth Coalfield determined that the coal was mainly bituminous types with low ash, low moisture and high swelling properties (Suggate, 1959; Sara, 1963; Suggate, 2012; Newman, 1985; Li, 2002). Therefore, the coal in Greymouth Coalfield is generally considered good quality and is often mixed with lower rank coal for export.

However, the Greymouth Basin is not only associated with coal. Core drilling and coal exploration around Kotuku and Lake Brunner uncovered signs of oil seeps and petroleum shows within drill holes (Morgan, 1911; Nathan et al., 2002; Beggs, Ghisetti, & Tulloch, 2008). Although this area has been under investigation for over a century, no significant petroleum play has been found. Geochemical analysis has been conducted on the composition of the Kotuku oil seeps, and they have a very high abundance of C29 ββ steranes, indicating a fully terrestrial, coaly source organofacies (Zink & Sykes, 2010). These seeps are similar/analogous to the Maui oil family in the Taranaki Basin and are derived essentially from the fully terrestrial Paparoa sequence (Zink & Sykes, 2010). Oil seep occurrences are not rare but uncommon, with notable occurrences in the Cretaceous Paparoa Coal Measures from various mines (Young, 1967). The identification of terrestrial biomarkers within the oil seeps, indicate that they are derived from a similar source to the Cretaceous aged abundant oil fields in Taranaki (Hirner & Lyon, 1989; Frankenberger, Brooks, Varela-Alvarez, Collen, Filby, & Fitzgerald, 1994).

With the similarities in basin formation and potential source rock characteristics of the Taranaki Basin and the Greymouth Basin, the Paparoa Coal Measures should be considered as a potential location for economic hydrocarbon production. The data collected from the Paparoa Coal Measures can be applied to the Taranaki Basin to gain a better understanding of the sediments, due to the lack of data available in Taranaki. The investigation of this study into a possible reservoir rock in the Greymouth Coalfield, is another step in the direction of determining the petroleum potential in the Greymouth Basin.

However, no commercially economic quantities of hydrocarbons have been discovered within the Greymouth Coalfield or surrounding areas yet, but there are drilling operations by Mosman Oil and Gas exploring the Kotuku anticline with early results showing minor oil and gas shows.

There has been no research into the potential reservoir rocks the Paparoa Coal Measures hold, in the Greymouth Coalfield.

1.4 Geologic Setting

The Greymouth Basin has been thoroughly investigated with respect to the characterisation of the coal bearing deposits. This leaves the other sedimentary lithologies and any petroleum aspects under studied, unless they are directly influenced by the coal (Newman, 1985, Newman and Newman, 1992; Ward, 1997). The Greymouth Basin consists of mainly the Paparoa Coal Measures (Nathan et al., 2002).

The Paparoa Group (Figure 1.2) comprises seven members according to their different lithologies and sedimentary facies (Nathan et al., 2002). The members are (stratigraphically oldest to youngest) the Jay, Ford, Morgan, Waiomo, Rewanui, Goldlight and Dunollie. These slightly differ lithologically and spatially across the Greymouth Basin.

The conglomerates, sandstones and mudstones within the Paparoa Formation will be the subject of this thesis, and are known as the Jay, Morgan, Waiomo, Rewanui, Goldlight and Dunollie Members (Figure. 1.2). These members outcrop at only a few accessible locations throughout the basin, with the main outcrop of the north-west section, next to 10 Mile Creek and along 12 Mile Beach. Drill cores from around the basin were also looked at, particularly in the east of the basin where outcrops are more scarce.

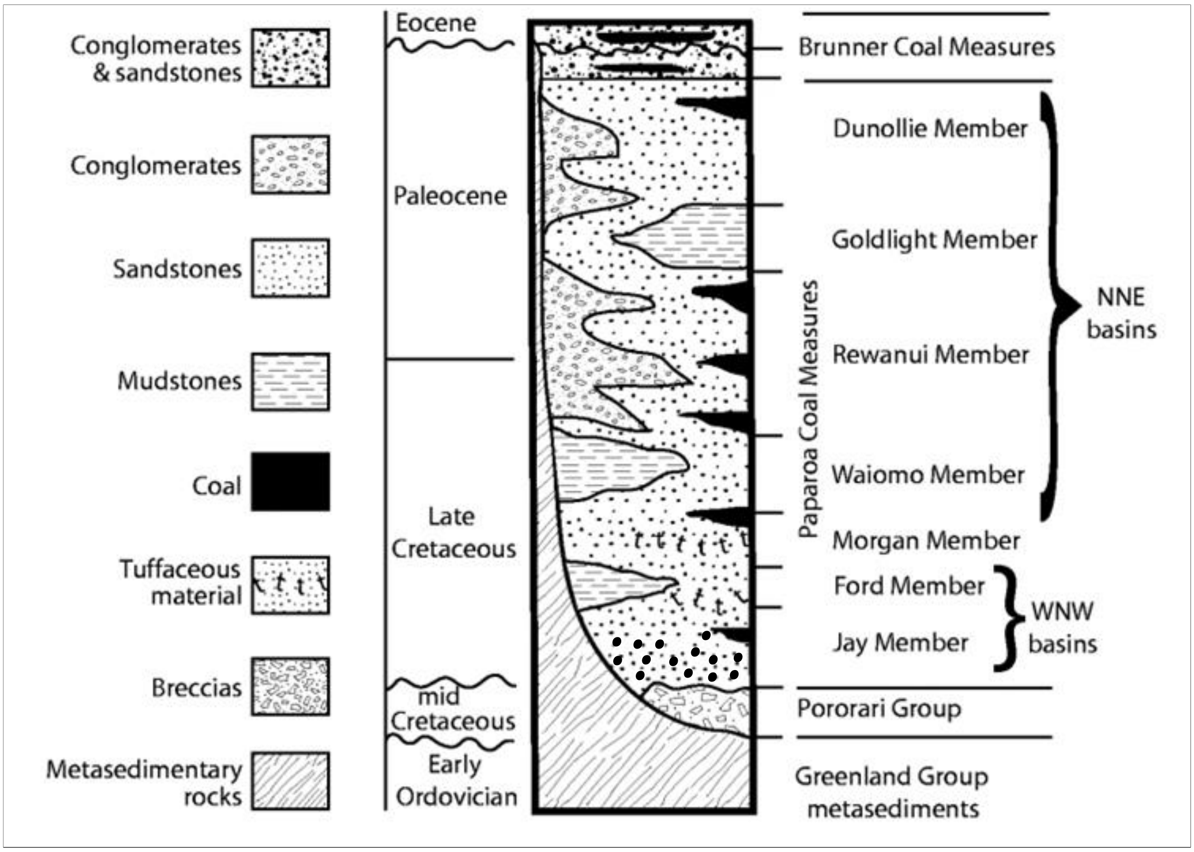

Figure 1.2 Stratigraphic Succession of Paparoa Formation (Edited from Bassett, Ettmuller, & Bernet, 2006)

The Papoaroa Coal Measures stratigraphy has been redefined multiple times throughout the past 100 years. This has led to numerous different categorisations and complex amalgamation of members and formations. Currently there are five formations and three members, the Jay, Ford, Rewanui, Goldlight and Dunollie Formations and the Morgan, Waiomo and Rewanui Members of the Rewani Formation (Table 1.1) (Nathan, 1978; Newman, 1985; Ward, 1997; Nunweek, 2001). For the purpose of this research, names will be simplified, and all constituent members will be raised to formations. This follows Gage's original classifications before the changes in Nathan, 1978. The reason behind the name changes made by Nathan (1978) was that the Paparoa Coal Measures are constrained to the Greymouth Coalfield only. However, based on the criteria of a formation (Boggs, 2006), a body of rock that is identified by lithology and is mapable at the surface and subsurface, the demotion to member for some units is superfluous.

<table>
<tr><th colspan="5">Paparoa Coal Measures Nomenclature</th></tr>
<tr><th>Gage, 1952 / Cody, 2015</th><th colspan="2">Nathan, 1978 / Newman, 1985 / Nunweek 2001</th><th colspan="2">Ward, 1997</th></tr>
<tr><td>Dunollie Formation</td><td>Dunollie Coal Measures Member</td><td rowspan="9">Paparoa Formation</td><td>Jay Formation</td><td></td></tr>
<tr><td rowspan="2">Goldlight Formation</td><td rowspan="2">Goldlight Mudstone Member</td><td rowspan="2">Goldlight Formation</td><td>Goldlight Formation</td></tr>
<tr><td>Goldlight Transitional Member</td></tr>
<tr><td>Rewanui Formation</td><td>Rewanui Coal Measures Member</td><td rowspan="3">Rewanui Formation</td><td>Rewanui Morgan Coal Measures Member</td></tr>
<tr><td>Waiomo Formation</td><td>Waiomo Mudstone Member</td><td>Waiomo Mudstone Member</td></tr>
<tr><td>Morgan Formation</td><td>Morgan Coal Measures Member</td><td>Morgan Coal Measures Member</td></tr>
<tr><td rowspan="2">Ford Formation</td><td rowspan="2">Ford Mudstone Member</td><td rowspan="2">Ford Formation</td><td>Ford Formation</td></tr>
<tr><td>Ford Transitional Member</td></tr>
<tr><td>Jay Formation</td><td>Jay Coal Measures Member</td><td>Jay Formation</td><td></td></tr>
</table>

Table 1.1 Table of Paparoa Coal Measures nomenclature and revisions.

With the numerous studies undertaken on the Greymouth Basin focused on the coal measures, the first major investigation into the Greymouth Basin was by Maxwell Gage (1952).

Maxwell Gage published the first comprehensive investigation into the Greymouth Basin. Gage (1952) divided the Paparoa Coal Measures into seven formations of alternating lacustrine and fluvial deposits as well as identifying the lateral changes in thickness and lithofacies which contributed to the very complex stratigraphy (Newman, 1985). Gage was responsible for the extremely thorough mapping of the coalfield providing details on structural and stratigraphic information on the region that is still used today. Gage inferred the paleo-environment as well, he visualised the basin as a north trending, rapidly subsiding trough being feed by a western granitic and an eastern Greenland Group basement source, with a history of lacustrine transgression and regression (Newman, 1985). Gage's work remains the basis and first step in any new research done in the Greymouth Coalfield.

Nathan (1978) published the next geological map of the Greymouth district to a 1: 63,360 scale. Although Nathan extended and expanded previous work on the Tertiary marine lithologies, his published map was essentially a reproduction of Gage's previous maps. Nathan did make changes to the stratigraphic nomenclature demoting the formations to members. He stated that since the formations could only be recognised in the Greymouth area and pinch out locally, that they should be defined as a member (Newman, 1985). Since then it is now possible to hesitantly correlate the Paparoa Coal Measures between Greymouth and Pike River Coalfields based on lithologies (Newman, 1985). However, there is no paleo botanical evidence at present to substantiate this correlation. The revisions Nathan proposed to the stratigraphic nomenclature are now generally used by the coal industry, but both Gages and Nathans categorizations are still used today

Newman (1985) was the next extensive research to investigate the Greymouth Coalfield. Newman unsurprisingly focused on the coal and the relationship between the Brunner and Paparoa Coal Measures, as well as the paleo environment. This study summarised in Newman (1987) and Newman & Newman (1992) expanded the knowledge of coal petrology, paleoenvironmental analysis and geochemistry (Ward, 1997). However, Newman's investigations into paleo environment produced some interesting and compelling results in reference to provenance of the Paparoa Coal Measures.

Since Newman (1985), there have been multiple investigations into the Paparoa Coal Measures but none focusing solely on provenance until Bassett, Ettmuller, & Bernet, (2006). Bassett et al. (2006) focused on using SEM-cathodoluminescence and petrographic characteristics to investigate the provenance of fluvial/lacustrine quartz-rich lithic arenites in the Paparoa Coal Measures. The investigation revealed that the two main sources of sediment were the metasedimentary Greenland Group and a plutonic source. This study also suggested strike slip movement, as predicted by previous tectonic models. This study however, focused primarily on the finer sandstone clastics and did not incorporate the mudstones or coarser conglomerate clastics.

The most recent investigation into the Paparoa Coal Measures was undertaken by Emma Cody (2015). Cody (2015) looked at the sedimentology and hydrocarbon potential of the Paparoa Coal Measures lacustrine mudstones. The investigation determined that potential hydrocarbon bearing lacustrine source rocks exist in the Greymouth Coalfield. Therefore, Cody's research now provides any future investigations into the Greymouth Basin as a petroleum play, with another possible source rock other than the coal seams (Cody, 2015).

1.5 Lithological Summary

Seven formations comprise the basins evolution; Jay, Ford, Morgan, Waiomo, Rewanui, Goldlight and Dunollie formation (Figure 1.2). The Jay comprises primarily of conglomerate on the western side of the basin, with some, sandstone, mudstone and coal (Gage, 1952; Nathan, 1978; Newman, 1985; Newman & Newman, 1992; Ward, 1997) The Ford comprised primarily of mudstone and was the first of the lacustrine environments within the basin (Gage, 1952; Nathan, 1978; Newman, 1985; Newman & Newman, 1992; Ward, 1997; Cody, 2015).The Morgan is dominated by conglomerate on the west side of the basin with some volcanic, sandstone and mudstone influence on the eastern side. The Waiomo formation is the second, and one of the more significant lacustrine deposits being spatially consistent across most of the basin (Gage, 1952; Nathan, 1978; Newman, 1985;

Newman & Newman, 1992; Ward, 1997; Cody, 2015). The Rewanui consists of thick sequences of poorly sorted, pebble to boulder, polymictic conglomerate in the west, with fine to coarse grained sandstone in the east of the basin (Gage, 1952; Nathan, 1978; Newman, 1985; Newman & Newman, 1992; Ward, 1997). The Goldlight is the last of the lacustrine deposits and is the second spatially consistent, being found over the majority of the basin (Gage, 1952; Nathan, 1978; Newman, 1985; Newman & Newman, 1992; Ward, 1997; Cody, 2015). The last formation, the Dunollie formation is dominated by thick sequences of poorly sorted, pebble to boulder, polymictic conglomerate in the west, and fine to coarse grained sandstone in the east of the basin, just like the Rewanui formation (Gage, 1952; Nathan, 1978; Newman, 1985; Newman & Newman, 1992; Ward, 1997).

1.6 Controversies

The main controversy that this study is investigating is the issue of sediment source and location of sediment source relevant to the basin. Gage (1952) believed that there was a granitic source to the west and a Greenland Group source to the east. Gage (1952) summarised his interpretation of Rewanui paleogeography as follows: "An abrupt change to coarse sediments succeeding the Waiomo lake deposition suggests a sharp elevation of a neighbouring area, and from the observed regular increase in coarseness towards the north-west it is inferred that the source of the sediments lay in that direction. Granite-derived waste makes up the greater part of the Rewanui beds, in place of the Greenland Group material that characterised the lower coal measures, so that it may be inferred also that the north-western source area consisted of granite mountains" (Gage, 1952).

Newman (1985) suggested that the Rewanui sediments had a granitic source but it was located to the east of the basin, with the well exposed conglomeratic facies in the north-west, largely Greenland Group derived. Newman (1985) believed that the quartzose sandstones on the eastern side of the basin, is full of granitic source detritus deposited by fluvial systems along the main axis of the faulting. Indicating that the north-western source area consisted primarily of Greenland Group with only minor granite, contrary to Gage's interpretation (Newman, 1985). Newman (1985) states that she believed that Gage (1952) was wrong and that the opposite was true, with fluvial systems along the main axis of the faulting dominating the sediment deposition.

With Newman's (1985) investigations pointing to a main granitic source in the east and a predominantly Greenland Group source to the west, contradicting Gage (1952), this becomes a serious problem for the provenance of the Paparoa Coal Measures. Since then, there has been some tentative steps taken in determining the sources of the sediment in the Greymouth Basin with the most recent being Bassett et al. (2006).

There are two possible main sources of sediment for the majority of the Paparoa Coal Measures with the possibility of one other source. The two main suspected sources are the Greenland Group basement rock, and a granitic Karamea Suite source. The basement for the majority of the West Coast of the South Island of New Zealand including the Greymouth Coalfield comprises of Paleozoic Greenland Group greywacke and argillite (Nathan, 1978). The Greenland Group sediments formed as an accretionary wedge on the convergent margin of Gondwana. Sedimentation was dominantly the product of turbidite activity, driven by the transport of weathered sediments off the Gondwana continental block (Roser, Cooper, Nathan, & Tulloch, 1996).

There are a few possible granitic sources that could be birthplace of the granitic clasts and sediment. Large granitic intrusions into basement sediments occurred during the Middle-Devonian (Nunweek, 2001). This suite of granitoids is known as the Karamea Batholith, which intruded the Greenland Group approximately 370 ± 5 Ma. (Muir, Ireland, Weaver, & Bradshaw, 1992; Muir, Ireland, Weaver, & Bradshaw, 1994). The younger granitic intrusions like the Rahu Suite occurred between 120 - 110 Ma (Muir et al., 1994). These granitic bodies show a younging relation towards the west, from the Separation Point Batholith (119 Ma ± 2.3 Ma.) in the east, to the Buckland Granite in the west (109 ± 4 Ma.) (Muir et al., 1994). The widespread intrusion of these granites throughout the Greenland Group, makes them one of the dominant rock types of the West Coast basement.

However, there is a large metamorphic and gneissic component to the geology of the West Coast due to the Paparoa Metamorphic Core Complex. The core complex exposed and caused a lot of deformation in the surrounding rocks. The Charleston Metamorphic Group at Charleston is composed of two main Early Cretaceous lithologies, paragneiss and orthogneiss (Kimbrough & Tulloch, 1989). Although, these lithologies are not as wide spread as the Greenland Group and granites, the ages of them make them temporally consistent with the beginning of the Greymouth Basin's development and the initial deposition of the Paparoa Coal Measures.

1.7 Aims of this Work

Past research has focused predominantly on the coal and coal bearing units for economic reasons. Little research has been conducted on the non-coal bearing units, such as the conglomerates and sandstones in the Paparoa Coal Measures. Provenance and sedimentology of the non-coal bearing units provide insight into basin history, development and geometry. Petroleum interest and exploration in New Zealand has increased in the past decades especially in the Greymouth region. The interest in the Greymouth area is due to the similarities in basin characteristics to the proven economic viability of the Taranaki oil field. Oil shows in the Paparoa Coal Measures are known, indicating the presence of a working petroleum system (Cody, 2015; Gage, 1952; Nathan et al., 2002).

The aim of this research is to address the provenance of the sandstones and conglomerates of the Paparoa Coal Measures as well as their porosity in relation to a possible petroleum reservoir. This will address the main controversy surrounding the source rock that has been mentioned between Gage (1952) and Newman (1985) (Gage, 1952, Newman, 1987, Newman & Newman, 1992) as well as provide a better understanding of the non-coal bearing units and their relevance to the West Coast-Taranaki rift. The provenance investigation will also be used to produce the basin geometry. The basin geometry will provide more information regarding the petroleum prospects in the region as petroleum exploration is active in New Zealand, which makes this research relevant.

In Summary:

- Identification of provenance of Paparoa Coal Measures conglomerates and sandstones.

- Reconstruction of a paleogeographic setting and basin geometry.
- Determine porosity in the sandstones and whether the sandstones in the Greymouth Coalfield are potential reservoirs for hydrocarbons.

This thesis will address some previously unresolved questions and unsubstantiated claims about the sediment sources of the Paparoa Coal Measures in the Greymouth Basin. The research will also indicate whether the Paparoa Coal Measures contain a prospective reservoir, requiring more investigation in reference to petroleum prospects.

Chapter 2 Methods

A number of analysis techniques were used in this study including field work and laboratory analysis. The majority of the field work was focused around the north-west of the basin with a few outcrops in the centre and east side of the basin. Field work was limited as outcrop was difficult to access in the majority of the basin. However, there are a few locations in the east were outcrop was accessible with the assistance of drill core samples. The majority of data collected came from drill core and was sampled from across the basin to supplement outcrop data. Measurements and clast counts were recorded and taken from the New Zealand Petroleum and Minerals Core Store in Featherston, New Zealand.

2.1 Sedimentary Description

2.1.1 Sample Locations

Field work was undertaken over several months in 2016 and 2017 focusing primarily around the north-west of the coalfield just north of the Greymouth Township. Outcrops within the Greymouth coalfield were limited with dense vegetation, steep topography and high rainfall causing high risk of flash floods in rivers and streams. The main outcrop for the Paparoa Coal Measures was along the coast of 12 Mile

Beach but the Paparoa Creek, 7 Mile Creek and 10 Mile Creek were also visited (Figure 2.1).

The Paparoa Creek runs next to a small town called Blackball, located east of the Greymouth Basin. The Paparoa Creek provided access to an outcrop of the Morgan igneous conglomerates or the Morgan Volcanics (Gage, 1952), which elsewhere is non-existent (Figure 2.1). The creek is quite remote with dense vegetation, steep topography on both banks, and sections of sandstone gorge with deep water that had to be swum. The Morgan Volcanics were approximately 4.5 km up stream, and there was no Global Positioning Satellite (GPS) reception due to the location, topography and dense vegetation.

7 Mile Creek runs past Spring Creek Mine with an access road to Mount Davy. Due to the mine being on standby the access road was closed. The walk to the bottom of the Goldlight formation was approximately 2km from the Spring Creek Mine Gate, and the Goldlight samples were obtained from there (Figure 2.1).

10 Mile Creek was visited but access was restricted. Nothing of interest was observed when walking up the track for a couple of hours (Figure 2.1).

12 Mile Beach has a large exposed section of the Paparoa Coal Measures outcropping as a cliff face along a large stretch of the beach (Figure 2.1). This allowed for a thorough investigation of the conglomerates and the stratigraphy dependent on the tides and variable weather. Any field work at 12 Mile Beach was heavily reliant upon the tides due to health and safety concerns.

Because of the dense bush, terrain and scarce outcrops in the Greymouth coalfield, drill core from the area was used as well. The drill core from this area is stored in the New Zealand Petroleum and Minerals Core Store in Featherston, New Zealand.

The drill core sampling was based on a spatial distribution of sampling across the basin, and the availability of core held at the New Zealand Petroleum and Minerals (NZP&M) core store in Featherston. The NZP&M core library was used because many of the cores from newer drill holes are not retained. This meant that although the drill cores are older, they are accessible for sampling and are more evenly distributed across the coalfield.

Multiple drill cores from across the area were chosen, to provide the best spatial and stratigraphic representation of the Greymouth coalfield (Figure 2.1). Drill holes 620, 632, 634,649 and 660 were examined along with samples and clast counts taken where appropriate. Drill hole 634 was chosen as this drill core was located from the north-west corner of the basin. This specific core was selected to represent the north-west corner of the basin, as it encountered a large portion of the Rewanui and Dunollie formations. Drilling of this core stopped at 559.3m as warm artesian water and gas was encountered. Core 649 was examined as it was taken from the south-west of the basin and intersected four of the Paparoa Coal Measures (Jay, Rewanui, Goldlight and Dunollie formations), all the way down into Greenland Group basement at 384.4m. Drill hole 632 is located in the middle which subsequently cuts down into the middle of the basin. Drill hole 632 was selected due to its location and because it intersects five of the Paparoa Coal Measures lithologies (Jay, Waiomo, Rewanui, Goldlight and Dunollie formations) before hitting Greenland group basement at 673.1m down. Drill hole 660 was taken from the north-east corner of the basin and chosen because of its location and the core intersects six of the Paparoa Coal Measures (Jay, Ford, Morgan, Waiomo, Rewanui and Goldlight formations), stopping at 478.0m in the Jay formation. Drill hole 620 lies in the South-east corner of the basin and was selected because of its location, and because the core intersects all seven of the Paparoa Coal Measures (Jay, Ford, Morgan, Waiomo, Rewanui, Goldlight and Dunollie formations) ending in the Jay formation at a depth of 800.9m.

The measured section of the Paparoa Coal Measures was conducted at 12 Mile Beach (Figure 2.1). This was an extensive outcrop of almost all of the coal measures. However, there are a few formations that were not present along 12 Mile Beach. The Jay, Ford and Goldlight formations are missing from this out crop.

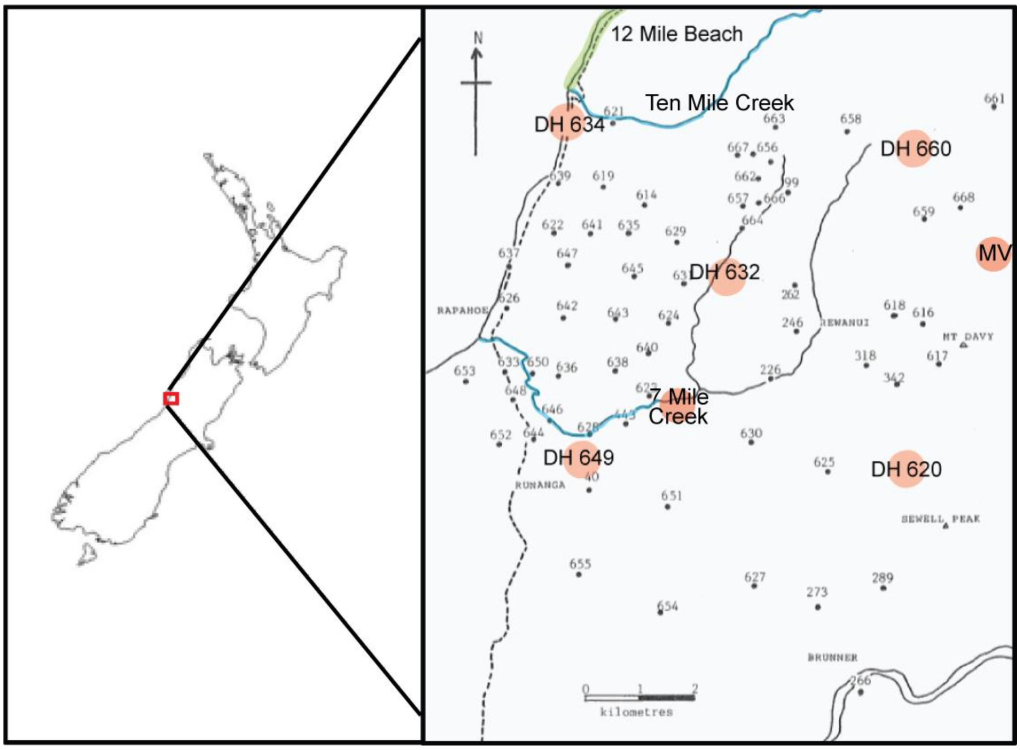

Figure 2.1 Outcrop locations and drill hole locations (MV for Morgan Volcanics).

2.1.2 Measured Section

The section was measured along the beach using a metre ruler and a GPS device for precise locations. The section was measured from the basement Greenland Group up section to the top of the Dunollie formation. The contact between the top of the Dunollie and base of the Paleocene Brunner was covered in rock fall. Bed thicknesses were predominantly directly measured in metres and trigonometry was used to calculate measurements only in small sections of rock fall or covered outcrop.

A few faults were observed with offset and movement directions also recorded along with strike and dip of fault plane.

The 12 Mile section was measured to help create a model of the paleo environment through time as the Paparoa Coal Measures were deposited and the basin geometry of the Greymouth Basin.

2.1.3 Descriptions of Individual Outcrops and Cores

At outcrop standard descriptions of structure, texture and compositions for each outcrop or bed were taken along with contact descriptions and any measurements, bedding or cross bedding and strike, recorded. Along the 12 Mile Beach section, each bed was investigated throughout for changes in structure, texture, composition which could therefore indicate changes in deposition.

The drill hole cores had been previously logged and described during the drilling. The Drill Hole Summary logs provided by the company who drilled the hole were compared with the core continuously throughout and were consistently accurate and provided in depth descriptions of the core.

2.2 Conglomerate Clast Provenance

The aim of the provenance of the conglomerate clasts is to determine the sources of the conglomerate constituents. This will be determined by a number of analysis techniques; samples of the clasts encountered will be collected for further analysis, clast counts to determine percentage of constituents, petrographic analysis to provide a more detailed identification and geochemical analysis to provide a detailed composition. These techniques and analysis will allow for determining the source of the clasts.

2.2.1 Sampling in the Field and Core

Clasts sampled were; metasandstone, hornfels, quartz, granite, argillite, aplite, mudstone, basalt and white brecciated clasts. Clast samples taken were a representation clast sample for all clasts.

The clast samples were taken from outcrop with a rock hammer. The clasts were usually well indurated as was any matrix surrounding them. This resulted in clast fragments more than whole clasts. Due to the nature of the clast being exposed on the outcrop, weathering was an issue. However, the least weathered samples were chosen where possible. Each sample taken was put in its own labelled bag along with date, time, GPS coordinates, clast type, formation and sample number.

Clast samples taken from the drill core were slightly more difficult to collect. Multiple samples of any granitic clasts were taken to determine if they all came from the same source. The clasts were cut out of the core with a diamond edged saw while drill hole number, date, formation, depth, sample type, sample number and a brief description of the sample was recorded on the sample bag and in a note book. All samples cut from the core were done by Dan Willmott the storeman at the Featherston Core Store, and were approximately 5 cm long each.

Clast samples were taken for thin section and a few for geochemical analysis for determination and confirmation of the lithologies represented in the clast counts. Confirming clast composition was crucial for determining provenance and proportions of sediment sources for each count.

2.2.2 Clast Counts

Clast Counts were conducted both in the field at 12 Mile Beach and with the drill core at the NZP&M Core Store in Featherston (Figure 2.2). A metre ruler was used and placed against the outcrop or core. A clast count was conducted at every one centimetre interval along the metre ruler. However, if the same clast intersects more than one centimetre interval, it was dismissed to avoid double counting. The clast types were described and recorded in the field or core whenever a new type of clast was intersected and encountered. The clast counts were tallied aside corresponding clast name. This continued for a minimum of 100 clasts counted where possible.

However, there were a few drill cores where 100 clasts were not present. Clast counts were conducted along a horizontal plane where possible but with the drill cores the counting had to be vertical. These clast counts were sampled parallel to the bedding plane where possible, with the exception of the vertical drill cores. Wherever viable, clast counts were taken near the base, middle and top of the formation to see if there was a change in dominant source temporally.

This method provided statistical information on the proportion of minerals, to identify the abundance of sediment sources in the catchments and paleo-environment at the time of deposition (Johnsson & Basu, 1993). The information provided from this method will help to determine the provenance of the coarser clastic sediments.

Figure 2.2 Core descriptions, measurements and clast counts. Featherston Core Store, Jay formation, DH 620 Depth ~786m.

2.2.3 Petrographic Identification

Representatives of the clasts identified within the conglomerates were sampled and thin sections were made. Thin sections provide a more accurate description of the clast, composition, minerology and were used, to help distinguish and eliminate any uncertainty between hand samples and clast counts.

Sandstone samples were also made into thin sections for staining and point counting analysis. Thin sections of the sandstone samples allowed for a more accurate investigation into composition and minerology.

The sample has a very thin slice cut off of it to be glued onto a glass slide. The thin slice of the sample is cut to approximately 0.03mm thick. This allows the light to travel through the crystals or grains in the sample. No top glass slide was glued on to allow for feldspar staining. The thin section is examined under a petrographic microscope, in both plain polarized light and cross polarised light at different magnifications. Minerals, mineral quantities and textures were identified due to crystal properties that were observed.

Multiple types of petrographic microscopes were used to investigate the thin sections, a Carl Zeiss Einbau Trafo, a Meiji model MX9200 and a Leica model DMEP petrographic microscopes. The three types of microscope were used because the Carl Zeiss Einbau Trafo had the best lenses, the Carl Zeiss Einbau Trafo and

Leica model DMEP both had the point counter attached and the Meiji model MX9200 was used as it was a binocular microscope and was easier to look through for sustained periods of time.

Thin section and petrographic identification is one of the more accurate ways of determining mineral composition of the lithologies. Petrographic analysis provides an in depth understanding of composition and formation of the samples, which assists with the provenance of the sample and basin as a whole.

2.2.4 Igneous Clast Geochemistry

Before the geochemistry analysis could be undertaken the samples had to be prepared. Geochemical analysis requires samples be crushed into a fine powder before being analysed. Therefore, the samples were subsequently crushed using a RockLabs vibrating tungsten carbide ring crusher (Figure 2.5).

The crusher was set to run for 30 seconds, at which point it turned off and enabled the tungsten carbide ring container to be removed. The lid was removed as well as the rings enabling any powdered residue to be scraped off, and placed back into the container. The sample powder was then carefully transferred into a sample bag with a piece of clean folded paper, to reduce any risk of contamination. The sample was then labelled appropriately, with the same label identifier as the solid rock, noting exactly where it had originated.

After use, the crushing container and rings were thoroughly washed with warm water and then dried to prevent contamination for future samples (Figure 2.5).

X-ray fluorescence (XRF) is a non-destructive analysis used to determine the elemental composition of materials. XRF determines the chemical constituents of a sample by measuring the fluorescent X-ray emitted when it is excited by a primary X-ray source. Each element present in a sample produces a set of characteristic fluorescent X-rays, which are unique to that element. This fingerprint is why XRF is excellent for qualitative and quantitative analysis of material composition.

XRF analysis was conducted on multiple samples of different lithologies; granites, basalts and some volcanics.

The crushed samples were sent to an outside laboratory to be analysed, due to the University of Canterbury's XRF equipment and lab being closed for 6 months and moved to a new building. The outside laboratory chosen by the University of Canterbury's XRF technician, was Spectra Chem. Spectra Chem is a company owned by CRL Energy Ltd and they specialise in the X-ray fluorescence and X-ray diffraction analysis of a wide range of inorganic and organic materials, such as rocks and soils, plant and animal tissue, metal alloys, industrial wastes, oils, plastics and polymers. Their clients include mining and geological exploration companies, environmental consultants, oil and manufacturing industries, and research organisations. They are also the only IANZ (International Accreditation New Zealand) accredited, independent XRF specialists in Australasia.

The powdered samples were all oven dried to 110°C to reduce the water and other volatile components and loss on ignition (LOI). The samples were then analysed for a complete major and trace element suite, analysis including Large Ion Lithophile Elements (LILE) and High Field Strength Elements (HFSE). Rare Earth Elements (REE) analysis was also conducted to a limited degree, with only a few REE's analysed. Major elements analysed were; SiO_2, TiO_2, Al_2O_3, Fe_2O_3, MnO, MgO, CaO, Na_2O, K_2O and P_2O_5. Trace elements and REE's analysed were: As, Ba, Ce, Cr, Cu, Ga, La, Nb, Ni, Pb, Rb, Sc, Sr, Th, U, V, Y, Zn and Zr.

The geochemical analysis of the clasts was utilised to determine the parent or source rock for the sediments. XRF analysis will determine the rocks chemical composition which will be compared to the chemical composition of sediment sources in the area and traced back to the source, almost like a chemical fingerprint (Peterson, 2009; Yan, Xia, Lin, Cui, Hu, Yan, & Zhang, 2007). Proportions of elements in the clasts will be compared to the proportions of elements in probable parent rocks as collected in Petlab (Strong, Turnbull, Haubrock, & Mortimer, 2016). The Petlab database is New Zealand's online national rock and analytical database. It provides locations, descriptions and analyses of rock and mineral samples from on-land New Zealand, the offshore New Zealand region, Antarctica and worldwide

(Strong et al., 2016). The XRF results will help to correlate clasts with source rocks, and help to determine the provenance of the sediments in the Paparoa Coal Measures.

2.3 Sandstone Provenance

The aim of the provenance of the sandstone is to determine the source of the sand grains. This will be determined by a number of analysis techniques; samples of the sandstones encountered will be collected for further analysis, point counts to determine percentage of constituents, feldspar staining and petrographic analysis to provide a more detailed identification. These techniques and analysis will allow for determining the source and porosity of the sandstones as well as determining a tectonic setting.

2.3.1 Sampling in the Field and Core

Multiple different sandstone beds were found in the field at 12 Mile Beach as well as in cores. These sandstone beds were sampled if they were substantial in thickness and of medium to coarse grainsize. These samples were used for point counting and porosity analysis. However, there were exceptions, if the ideal grainsize and thickness of bed was not available to sample, fine grained sandstones and thinner beds were also sampled. A rock hammer was used to break off a portion of the rock which was then put into the appropriate sample bag, along with details of GPS location and sample details recorded.

Sandstone sampling from core was completed in the same way as the other core samples were collected with a diamond edged saw cutting out a sample from the core. This was then recorded multiple ways with a hard copy of core number, depth, formation, date, sample number and a brief description of the sample in my note book and also on the sample bag, where the cut sample was stored.

The sandstone samples were used to perform further analysis and a more comprehensive evaluation of the lithology.

2.3.2 Thin Section Creation

The preparation procedure of the slides was exactly the same for both the sandstones as the clasts. The sample has a very thin slice cut off and then glued onto a glass slide. The thin slice of the sample is cut to approximately 0.03mm thick. This allows the light to travel through the crystals or grains in the sample. No top glass slide was glued on to allow for feldspar staining. The thin section is looked under a petrographic microscope in both plain polarized light and cross polarised light at different magnifications. Minerals, mineral quantities and textures were identified due to crystal properties that were observed.

Thin sections were created to provide a more accurate and in-depth petrographic assessment of the proportion and composition, of the minerals in the sandstones.

2.3.3 Feldspar Staining

The sandstone samples are stained to help with point counting. The staining method was conducted according to the methodology presented in Lewis & McConchie (1994). The thin sections were polished using 400-600 grade corundum powder before they were etched with hydrofluoric acid for approximately 25 to 30 seconds. This allows the feldspar crystals to uptake the stain more effectively. The sample was then immersed into a supersaturated solution of sodium cobaltinitrite ($Na_3CO(NO_2)_6$). The K-feldspar (orthoclase, microcline, sanidine) should then show a distinctive yellow stain. To stain the plagioclase feldspar, the sample was dipped into the $BaCl_2$ solution. The barium will attach to the calcium in the plagioclase. Several drops of potassium rhodizonate $C_6K_2O_6$ is then added with an eyedropper or micropipette and left for a few seconds until the plagioclase grains turn pink (Houghton, 1980). The degree of stain is proportional to the calcium content in the plagioclase and pure albite, will not stain.

The stains turn the plagioclase feldspar crystal pink and the alkali feldspar yellow (Figure 2.3). This makes quantitative analysis such as point counting quick and accurate (Lewis & McConchie, 1994). However, the staining does obscure some of the minerals other crystal details. Due to this fact, only half of each sandstone thin section sample will be stained, to allow the other half of the sample unobscured.

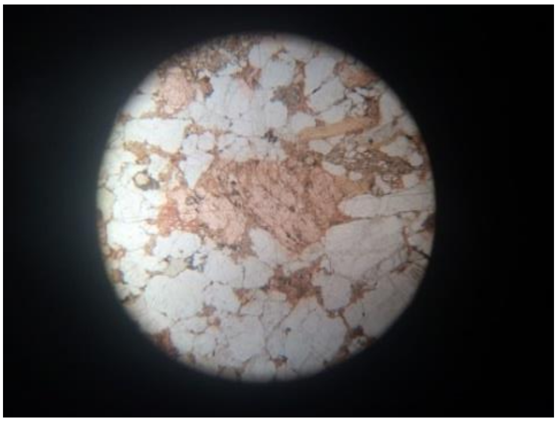

Figure 2.3 Stained Plagioclase feldspar in sandstone sample 84 from DH 632 in the Rewanui formation at a depth of ~415m.

The stain was added to help with the petrographic identification during point counting. Un-twinned feldspar, both plagioclase and alkali feldspar, are very similar to quartz in both plain and cross polarised light. The stain helps with faster and more accurate identification of these un-twinned feldspars (Figure 2.3). Therefore, the proportion of components for each sample is more accurate for determining provenance and tectonic setting.

2.3.4 Point Counting

The Gazzi-Dickinson method of point counting was used as it was developed to maximize source-rock data, while minimizing the time, effort, and expense of gathering such data (Ingersoll, Bullard, Ford, Grimm, Pickle, & Sares, 1984). Use of this method reduces and minimizes variation of composition with grainsize. Therefore, it eliminates the need for sieving and multiple counts of different size fractions (Ingersoll et al., 1984). This method can be used on any sand size and sorting allowing for a direct comparison between modern sands and poorly sorted ancient sandstones (Ingersoll et al., 1984). This, then allows for the direct relation of actual petrologic models in terms of composition to tectonic setting.

A unique aspect of this method of point counting is the assignment of sand sized crystals and grains within larger fragments to the crystal or grain category, instead of counting the larger fragment as one. (Ingersoll et al., 1984).

The stained sandstone slides are then placed under a Carl Zeiss petrographic microscope, with a point counter attached (Figure 2.4). The point counter used was a Pelcon with a 0.5mm step each count. The crystal grain that fell under the cross hairs of the microscope was identified and recorded, by pressing the corresponding button on the point counter keypad. The step horizontally and vertically was adjusted for a few samples, to avoid counting the same grain multiple times. However, if a grain was encountered twice, the step was skipped, to avoid counting the same grain twice. The method for determining the minerals, crystals and grains was staining, habit, twinning and cleavage, birefringence colours, relief, colour in plain polarised light and unique mineral characteristics, e.g. undulose extinction for quartz. The point counting data was put into 17 categories; undulatory quartz, polycrystalline quartz, strained polycrystalline, polysynthetic plagioclase, microcline alkali feldspar, stained alkali feldspar, weathered feldspar, muscovite, biotite, siltstone, mudstone, schist, basaltic, unknown lithic, opaques, matrix and organic fragments.

The three quartz categories, will help with determining if the source of the sandstones is plutonic or metamorphic (Basu et al., 1975; Basu, 1985; Cullers, Basu, & Suttner, 1988). Undulosity in quartz from low rank metamorphic rocks, is sufficiently different from that in pluton-derived quartz, to be useful in provenance interpretation (Basu et al., 1975; Basu, 1985; Cullers et al., 1988). This will be determined by plotting the corresponding quartz types on the graph, to see the amount of quartz, undulose quartz and polycrystalline quartz (Basu et al., 1975; Basu, 1985; Cullers et al., 1988).

The point count data will also be used to determine the tectonic setting of the basin. The relationship between sandstone compositions and tectonic setting was recognized through the work of Dickinson and Suczek (1979), and Dickinson et al. (1983). They showed that by plotting the detrital framework categories of sandstone suites on a QFL (Quartz, Feldspar, Lithics) ternary diagram, resulted in information about the tectonic setting of the depositional basins and their associated provenance (Dickinson et al., 1983). There is also a more specific QmFLt diagram which is similar to the QFL diagram, except that it plots exclusively monocrystalline quartz (Qm), and total polycrystalline lithics (Lt) (Dickinson et al., 1983). Dickinson and Suczek (1979) established that sandstone suites from different kinds of depositional basins, are a function of provenance types controlled by plate tectonics. Therefore, the point count data will help to determine the tectonic setting by the ratio of quartz, feldspar and lithics

The point counting analysis of the sandstones was conducted, in order to identify the proportion of minerals, to identify the abundance of source rock types in the catchments, and to determine tectonic setting.

Figure 2.4 Carl Zeiss petrographic microscope with point counter.

2.4 Mudstone Provenance

The aim of the provenance of the mudstone is to determine the source. This will be determined by geochemical analysis.

2.4.1 Sampling

Six mudstone samples were collected, three from each mudstone formation, obtained from the top, middle and base of the Waiomo and Goldlight formations. The Waiomo formation was sampled from the 12 Mile Beach outcrop. A rock hammer was used to break off a bit of mudstone and a sample was taken, being careful not to get any of the weathered surfaces. A rock hammer was also used to retrieve a clean, unweathered sample of Goldlight mudstone. The Goldlight samples were obtained from up Seven Mile Creek, just out of Dunollie, near the Spring Creek Mine. All samples were labelled and placed in snap sealed bags, to reduce any risk of contamination.

2.4.2 Geochemistry

For the mudstones samples, each sample was sealed in a plastic bag and broken with a rock hammer into smaller pieces for the rock crusher. The broken mudstone sample was then placed into the tungsten carbide crushing rings (Figure 2.5). The tungsten carbide rings are used, because they are very strong and do not contaminate the sample.

The mudstone sample fragments were subjected to the same process as the fragmented granite, basalt and volcanic clasts. The RockLabs crusher was set to run for 30 seconds, at which point it turned off and the tungsten carbide ring container could be removed. The lid and rings were removed to ensure that any powdered residue was able to be scraped off and placed back into the container. The sample powder was then carefully transferred into a sample bag, with a piece of clean folded paper, to reduce any risk of contaminating the sample. The sample was then labelled, with the same label identifier as the solid rock, noting where it was obtained.

After use the crushing container and rings were thoroughly washed with warm water and then dried to prevent contamination for future samples.

Figure 2.5 RockLabs Crusher and tungsten carbide rings, University of Canterbury.

The powdered mudstone samples in particular, were ashed and oven dried to 110°C, as they have a high organic component, before being analysed by XRF. The mudstone samples were prepared and analysed in exactly the same manner as other samples submitted for geochemical analysis.

The geochemical analysis of the mudstones was utilised to determine the parent or source rock, for the sediments. The trace elements and REE's (Rare Earth Elements) were measured to determine the type of source rock that the mudstones are derived from (Potter, Maynard, & Depetris, 2005). Th, Sc, and to a lesser extent Cr, are good indicators of sedimentary provenance, because they are quite in-soluble, and thus are transported, almost exclusively by terrigenous detritus. Therefore, they reflect the chemistry of their sources. Condie & Wronkiewicz, (1990); McLennan, Taylor, McCulloch, & Maynard, (1990), McLennan & Taylor, (1991) have favoured the use of plots, such as Th/Sc against Sc, and Cr/Th against Sc/Th as indicators of the proportions of felsic and mafic source rocks.

The most valuable trace elements in geochemistry are the rare earth elements or REE's, because they are not fractionated from each other by most sedimentary processes. They are largely insoluble under most geological conditions and therefore, are present in very low concentrations in river water and seawater (from 10×10^{-7} to 10×10^{-2} of the levels found in most rocks) (Potter et al., 2005). The REE's are released from primary minerals in the soil by weathering, but they are typically retained and concentrated within the weathering profile in secondary minerals (Nesbitt, 1979). Once eroded, these soil minerals then record the REE signature of the parent material (Potter et al., 2005). Clay minerals generally have a considerably higher total of REE concentrations than the coarser sized sediments and appear to be the most important mineral category in accommodating REE's in mudstones (Condie, 1991; Cullers, Barrett, Carlson, & Robinson, 1987). REE concentrations remain unaffected by most geological post depositional processes; diagenesis, for instance, typically has little influence on the redistribution of the REE, because very large water/rock ratios are required to effect any change in their sedimentary chemistry (Potter et al., 2005).

Therefore, mudstone geochemistry will help in the determination of sediment source for the mudstone which will also help with the overall provenance of the Paparoa Coal Measures in the Greymouth Basin.

2.5 Sandstone Porosity

Sand grains and particles that comprise sandstone reservoirs, usually never fit together perfectly due to the high degree of irregularity in shape (Tiab & Donaldson, 2015). The void space created throughout the beds between grains, called pore space or interstice, is occupied by fluids or gases. The porosity of a reservoir rock is defined as that fraction of the bulk volume of the reservoir, which is not occupied by the solid framework of the reservoir (Tiab & Donaldson, 2015).

The porosity of a sandstone is determined by the amount of empty space between the grains of sand. This empty space was determined by point counting the empty void space, to obtain a percentage of the rock that is empty.

In many thin section studies, particularly work associated with the petroleum industry, examination of the nature and the extent of porosity in the sediment, can be more important than the examination of mineral composition (Lewis & McConchie, 1994). Petrographic analysis of micro porosity in thin sections is difficult to examine in plain polarised light, and under crossed polarised light, the presence of grains in extinction makes porosity estimation almost impossible. The epoxy blue stain helped to facilitate the observation of pore space within the thin section. The degree of alteration to clays was also noted and considered, as it is detrimental to permeability and the overall capability and quality of the reservoir.

2.5.1 Sample Selection

Sandstone samples were chosen with two main criteria in mind; 1. A medium grainsize where possible and 2. A suitable thickness of bed. These criteria are a few of the primary indications of a possible reservoir rock, so samples were taken accordingly (Tiab & Donaldson, 2015). Due to availability, both fine and coarse-grained sandstone exceptions were sampled.

Eleven slides were selected for the blue epoxy stain as the main focus of this research was on provenance. A variety of different grainsize samples were chosen, keeping the reservoir criteria in mind, of a medium grained sandstone. This was because the basin had varying degrees of grainsizes throughout. Two drill holes 632 that sits in the middle of the basin and 660 in the north-east corner, which was primarily composed of sandstone.

2.5.2 Blue Epoxy Stain

The basic pore staining procedure involves using standard impregnation techniques, to fill the pores with an epoxy resin that has been mixed with a coloured fluorescent dye (Yanguas & Dravis 1985; Ruzyla & Jezek 1987).

The blue stain used to determine porosity was applied during the thin section construction process. The petropoxy blue dye was added and mixed with the epotek 301 resin. The blue coloured resin was then impregnated with a heated section to 65°C which was then used to make the thin section.

The void space was highlighted by the epoxy blue staining which helped in the quantification of void space.

2.5.3 Point Counting

The porosity point count was conducted with a simplified version of the previous sandstone point counts Gazzi-Dickinson method (Ingersoll et al, 1984). The counts only consisted of two categories, void space (blue dye) and not void space (grain). Quantitative analysis of the amounts of porosity can be made from standard point-count data, based on pore space abundance (Lundegard, 1992). The equipment and methodology of the counting, was the same as it was for the point counts (Figure 2.4). This determined the percent of the sample that was pore space vs grains (Dullien, 2012; Loucks, Reed, Ruppel, & Hammes, 2012; Houseknecht, 1987). The minimum count for the porosity was 424 counts with the average of 550.

The data acquired provided a percent of the rock sample that was pore space which is necessity for a potential reservoir rock in a petroleum play.

Multiple types of analysis techniques were undertaken, from field work to laboratory analysis. These techniques will help to determine the provenance, source, tectonic setting and porosity of the clastic sediments within the Paparoa Coal Measures. The results will also help to determine the basin geometry and paleo environment evolution of the Paparoa Coal measures in the Greymouth Basin.

Chapter 3 Stratigraphy

The Paparoa Coal Measures in the Greymouth Basin comprises a complete terrestrial sequence of alternating fluvial and lacustrine strata deposited in a Late Cretaceous to Early Cenozoic rift basin (Gage, 1952; Nathan, 1978; Newman, 1985; Newman & Newman, 1992). The stratigraphic and tectonic evolution of the Greymouth Basin was determined from the lithologic record from over 200 drill holes. This conclusion was supported by chronostratigraphic control from palynological identification of the Cretaceous-Tertiary Boundary (KTB) (Gage, 1952; Nathan, 1978; Newman, 1985; Newman & Newman, 1992; Ward, 1997). Basin fill comprises four distinct lithological facies, primarily distinguished by grainsize. Coarse polymictic conglomerate comprises the coarse clastic sediments within the basin. This lithology has pebble to boulder clasts, is poorly sorted, sub-rounded with lenses of sandstone, siltstone, mudstone and coal. This lithology has been interpreted as deposited by braided river fluvial and fan deltaic processes (Gage, 1952; Nathan, 1978; Newman, 1985; Newman & Newman, 1992; Ward, 1997; Bassett, Maitra & Steadman, 2016; Maitra & Bassett, 2016; Maitra & Bassett, 2017b). Mudstone is the second of the four distinct lithologies. Massive, silty mudstones with normally graded, thin fine grained, sandstone interbeds, rare plant fragments and freshwater bivalves. This lithology has been interpreted as lacustrine environments, within the basin (Gage, 1952; Nathan, 1978; Newman, 1985; Newman & Newman, 1992; Ward, 1997; Cody, 2015; Maitra & Bassett, 2017a). Interbedded sandstones and mudstones is the penultimate distinct lithologies. It comprises packets of moderate-well sorted, channelized, fine to medium grained, carbonaceous to non-carbonaceous, quartzose to lithic sandstone, interbedded with mudstone and conglomerate lenses (Gage, 1952; Nathan, 1978; Newman, 1985; Newman & Newman, 1992; Ward, 1997; Cody, 2015). This lithology is determined to represent a meandering river fluvial channel and floodplain, to low gradient deltaic environments (Gage, 1952; Nathan, 1978; Newman, 1985; Newman & Newman, 1992; Ward, 1997; Cody, 2015 Maitra & Bassett, 2016; Maitra &

Bassett, 2017b). The last of the distinct lithologies is interbedded fine siltstones and carbonaceous rich mudstones and coal beds. These lithologies are interpreted as floodplain and coal mires (Gage, 1952; Nathan, 1978; Newman, 1985; Newman & Newman, 1992; Ward, 1997; Cody, 2015, Maitra & Bassett, 2016; Maitra & Bassett, 2017b). These facies grade laterally into each other across the basin, with the conglomerates found primarily to the north-west, the mudstones in the centre and east, and the sandstones and coal in the centre and east, alternating with the lacustrine mudstones.

3.1 Lithostratigraphy

The Paparoa Coal Measures are composed of multiple different, temporally equivalent and spatially discontinuous lithologies across the basin found in the seven formations. The oldest basal formations are found in the east, with onlap onto basement and younging to the west (Gage, 1952; Maitra & Bassett, 2016; Maitra & Bassett, 2017b). This section summarises all the previous information, on each stratigraphic unit in the Greymouth Basin.

3.1.1 Basement

3.1.2 Greenland Group

The Paparoa Coal Measures in the Greymouth Coalfield rest unconformably on the Greenland Group of the Buller terrane, which is found along the majority of the West Coast of the South Island (Nathan et al., 2002). The Greenland Group characteristically consists of quartzose, relatively fine-grained, turbiditic sandstone and mudstone sequences of early Ordovician age (Adams, Harper, & Laird, 1975). These have been interpreted as oceanic deposits with turbidites, derived from the continent of Gondwana (Roser et al., 1996). The Greenland Group has undergone severe internal folding and faulting, occurring in the Early Silurian, when the Greenland tectonic event disrupted and deformed all the deposits within the province (Nathan et al 1986). At the same time, these very extensive basement rocks were subjected to low grade metamorphism to the green schist facies (Laird & Shelley, 1974).

3.1.3 Granites

Granitic intrusion into Greenland Group basement sediments, known as the Karamea Batholith, occurred during the Middle-Devonian at 370 ± 5 Ma (Muir et al., 1994). Barrytown granite and Meybille Bay granite are the closest representatives of the Karamea Suite, located to the north of the Greymouth Basin (Nathan et al., 2002). The Karamea Suite can be linked to episodes of granitic intrusion, in both Antarctica and Australia at similar times (Laird 1994; Mortimer, Rattenbury, King, Bland, Barrell, Bache, & Edbrooke, 2014). This indicates that the intrusion of granitic magmas was a regional Gondwana event and not specific, or localised, to the rocks of the West Coast of New Zealand.

The younger Early Cretaceous (120 -110 Ma) granitic intrusions of the Rahu Suite and Separation Point Suites, are linked to the break-up of Gondwana (Muir et al., 1994; Mortimer et al., 2014). These intrusions are widespread throughout the West Coast of the South Island, in the Greenland Group, making them one of the younger dominant rock types of the West Coast basement (Nathan et al., 2002). The Rahu and Separation Point Suites are geographically separated, with the Rahu Suite occurring further south and Separation Point Suite located in the north (Figure 4.16) (Waight, Weaver, & Muir, 1998). The Rahu and Separation Point granites, are commonly distinguished from the Karamea Suite by the lack of pink alkali feldspar megacrysts, the lack of biotite and abundance of muscovite in hand samples. The Buckland granite is the closest occurrence of the Rahu Suite to the Greymouth Basin, occurring within the Paparoa Metamorphic Core Complex.

3.1.4 The Charleston Metamorphic Group

During the separation of New Zealand from Gondwana and the opening of the Tasman Sea, the Paparoa Metamorphic Core Complex was developed during the first rifting system (Tulloch & Kimbrough, 1989; Herd, 2007; Schulte et al., 2014; Strogan et al., 2017). This rift event occurred before the formation of the Greymouth Basin, and deformed granites and exposed high grade metamorphic lithologies (Charleston Metamorphic Group) on the West Coast.

The Charleston Metamorphic Group (CMG) is composed of two main Early Cretaceous lithologies, paragneiss and orthogneiss (Kimbrough & Tulloch, 1989). The paragneiss is dominated by quartz, plagioclase, biotite, sillimanite and garnet assemblages (Kimbrough & Tulloch, 1989). There are rare amphibolite and calc-silicate nodules also present (Kimbrough & Tulloch, 1989). The paragneiss typically appears banded, with alternating quartzo-feldspathic and biotite-rich layers usually less than 10 mm thick, which are commonly sheared, folded, and boudinaged (Kimbrough & Tulloch 1989). The paragneiss represents metamorphosed sedimentary rocks, possibly Greenland Group.

Several granitoid orthogneiss lithologies occur at Charleston and predominate over paragneiss around Constant Bay, and indeed over the entire 12 km coastal section at Charleston. The two main types are biotite tonalite and two-mica granite. The biotite tonalite is weakly to strongly foliated, with tabular plagioclase producing a weak porphyroblastic texture (Kimbrough & Tulloch, 1989).

Other gneiss complexes occurring in the Westland and west Nelson regions have been grouped with the CMG, based on similarities in composition and metamorphic grade.

3.1.5 Pororari Group

The Greenland Group is predominantly the basement, however, in a few locations the Paparoa Coal Measures sit unconformably on the mid Cretaceous Pororari Group. Pororari Group alluvial fan sediments were deposited in the basins atop the Paparoa Metamorphic Core Complex (Kimbrough & Tulloch, 1989; Laird 1994). The thickly bedded breccia called the Hawks Crag Breccia, which lies within the Pororari Group, sits on top of the Greenland Group in a few locations (Nunweek, 2001; Ward, 1997). According to pollen dating these conglomerates/breccia were deposited approximately 112-99 Ma (Nathan, 1978). The mid-Cretaceous Pororari Group is related to the separation of New Zealand from Gondwana (Nathan et al., 2002; Laird, 1994; Laird & Bradshaw, 2004).

3.1.6 Paparoa Coal Measures and Paleocene Brunner

3.1.7 Jay Formation

The Jay Formation is the oldest formation within the Paparoa Coal Measures and is mainly composed of sandstones, conglomerates and thin coal seams. The Formation is subdivided into two units based on over all composition (Gage, 1952).

The Lower Jay is described as predominantly Greenland Group derived conglomerate, with occasional clasts of vein quartz, hornfels and quartzose sandstone (Gage, 1952). This conglomerate is usually sub-rounded to sub-angular, clast supported, with clast sizes of up to 25cm in the coalfield and in core samples, from the eastern side of the basin. There has been no evidence of granitic clasts within the Lower Jay.

The Upper Jay contains finer sandstones, and siltstones, with thin discontinuous coal seams and other carbonaceous horizons (Newman, 1985). The coal seams within the Upper Jay are generally dirty and low quality, making it economically unviable (Newman, 1985).

The conglomerate constituent of the Lower Jay Formation is primarily found throughout the centre and eastern side of the basin. The units are diachronous, with the Upper Jay sandstones overlying the Lower Jay conglomerate in the eastern part of the basin, being deposited at the same time as Lower Jay conglomerate, on the western side (Gage, 1952). Due to the economic agenda of drilling for coal-bearing lithologies, when the drill holes reached the lower conglomerate lithologies, the drilling stopped. This resulted in a lack of drill hole data for the lower formations in the western side of the basin, making it difficult to correlate from east to west.

The conglomerates of the Lower Jay were deposited by braided fluvial processes, while the Upper Jay in accordance to its finer sandstones and coal, formed in a lower energy flood plain environment (Newman, 1985).

The Jay Formation has been dated to approximately 71 Ma (Laird 1994), which is the same time that the Tasman Sea began spreading (Gaina et al. 1998). It has been noted, that the Lower Jay conglomerate can be hard to differentiate from the underlying Pororari Group which is found in the northern areas of the Coalfield (Newman, 1985).

3.1.8 Ford Formation

The Ford Mudstone is the first of the mudstones within the Paparoa Coal Measures. It was originally described as a brown grey to dark grey siltstone, with thin sandy laminations, approximately 60m thick (Gage, 1952; Newman, 1985; Ward, 1997). It has a distinguishing characteristic of an abundance of laminations within it.

Conglomerate lenses with Greenland Group metasandstone and quartz clasts are found in a few areas (Gage, 1952). Fossils within the Formation are mainly plant matter, leaf imprints, as well as some well-preserved land snails and freshwater molluscs (Gage, 1952). The presence of abundant organic material and freshwater molluscs indicates that the Ford Formation formed in a lacustrine environment, instead of a marine environment (Gage, 1952).

Outcrop and drill core data indicate that the Ford Formation is predominantly restricted to the eastern side of the basin, from Roa Mine to Spring Creek Mine (Gage, 1952). Ward's (1997) unpublished thesis revised the earlier interpretation, placing the Ford Formation at 12 Mile Beach instead of the Waiomo Formation. This was revised again with more recent work on 12 Mile Beach section, reassigning the mudstones there, to the Waiomo Formation (Nathan, 1978; Nathan et al 2002; Cody, 2015). Gage's (1952) interpretation therefore will be used in this thesis.

Lake inundation filled the depocentres during the deposition of the Ford Formation, which resulted in a small lake forming that was influenced by faulting (Newman, 1985; Gage, 1952; Ward, 1997). Interbedded sandstone and siltstone layers were caused by turbidity currents, which travelled down into the lake (Chang & Chun, 2012; Cody, 2015). The conglomerate lenses near the top and bottom of the formation are evidence for fluvial systems entering the lake. Also, these conglomeratic lenses indicate the beginning of the lake formation and the shallowing, as the lake transitioned back into fluvial processes (Ward, 1997; Gage, 1952).

3.1.9 Morgan Formation

The Morgan Formation consists of three very different facies; 1. Polymictic conglomerate, 2. Interbedded sandstones and coals, and 3. Basaltic volcanics with igneous clast conglomerate (Gage, 1952; Newman, 1985; Ward, 1997). The volcanics and igneous clast conglomerates are restricted to a small location in the east, near Roa Mine, and include basaltic lava flows and pillow lavas (Gage, 1952). The Morgan Formation here is unusually thicker than in other areas in the coalfield, with over 400 m of volcanic rock (Gage, 1952; Newman, 1985). Correlation between the Morgan Volcanics and basalts, found at Mount Camelback and the Ahahura-1 drill hole, gives an approximate age of 68 Ma (Laird, 1994).

The rest of the Morgan Formation is composed of predominantly Greenland Group derived conglomerates, similar to the Lower Jay Formation with clasts of; brown to grey sandstone clasts with weak bedding, quartz pebble clasts, fine carbonaceous mudstone and shale within the finer sections of sediment (Gage, 1952). The Morgan lacks any evidence of granitic clasts within the conglomerate (Gage, 1952). Workable coal seams are located within the Morgan, near the upper and lower transitions to mudstone with low ash and sulphur and high swell (Andrew Holley, 2015).

The Igneous clast conglomerate constituent of the Morgan Formation is restricted locally to the Roa Mine, whereas the polymictic conglomerates (Greenland Group, quartz, hornfels), are found throughout the east and north-west. The Morgan Formation becomes finer grained towards Spring Creek in the south-west, with more sandstone and carbonaceous horizons (Gage, 1952). The carbonaceous mudstone horizons can be seen at 12 Mile Beach, as the Morgan Formation transitions into the overlying Waiomo Formation.

Gage (1952) believed a volcano arose in the area near Roa and advanced towards the west, forming pillow lavas when it came in contact with the lake environment. The non-volcanic conglomerates in the other areas of the coalfields are thought to have been formed by erosion of the Greenland Group basement, and a possible recycling of unconsolidated Jay conglomerates. The remaining finer grained material was likely deposited by deltas that eventually filled in the Ford lake system, leaving a low lying plain and small raised mires and peat bogs (Gage, 1952; Nathan, 1978; Newman, 1985; Ward, 1997; Nunweek, 2001; Cody, 2015).

3.1.10 Waiomo Formation

The Waiomo Formation is described as a dark grey/brown, massive mudstone and siltstone (Gage, 1952; Newman, 1985; Ward, 1997). There are thin, normally graded sandstone beds, as well as lenses of polymictic conglomerate, at the gradational contacts with the under and overlying formations. Fossils, found in this formation were rare fresh water molluscs and occasional snail fossils, which are also found within the Ford Formation (Ward, 1997).

The formation is extensive, extending from the western side of the coalfield at 12 Mile Beach, across to Roa Mine, where it has been cut by the Roa – Mount Buckley Fault Zone (Gage, 1952; Nathan, 1978; Nathan et al., 2002). It is thickest in the north of the coalfield (up to ~60m thick), thinning to the south (30-50m thick) until finally pinching out in the south and south-west, where the upper highly gradational contact, meets the Rewanui (Newman, 1985; Gage, 1952).

The Waiomo Formation is interpreted to have formed in a lacustrine environment, due to the evidence of the massive mudstone facies, fresh water fossils and terrestrial snails found in drill core (Gage, 1952). This formation is interesting because it appears partly coeval with the Rewanui Formation, and the transition from lacustrine Waiomo to fluvial Rewanui deposition, was associated with important peat accumulation in some areas (Newman, 1985).

3.1.11 Rewanui Formation

The Rewanui Formation is the most economic unit in the coalfield containing the thickest coal seams. The Rewanui coal seams are found throughout most of the coalfield, primarily the east, with mining currently happening at Strongman and Roa Mines. The coal seams can be up to 10m thick, with most of the coal occurring near the top and bottom of the formation (Newman, 1985; Suggate 2012; Ward, 1997).

Newman (1985) divided the Rewanui into compositional suites, Eastern and Western, based on lithology and source area (Newman, 1985, Ward 1995). There is no defined contact between the Eastern and Western Compositional Suites, as the actual contact has yet to be identified (Ward, 1997). Therefore, there is only an arbitrary contact between the two compositional suites.

The Eastern Compositional Suite consists of mainly micaceous sandstone, with current indicators (cross bedding, channels and ripples) and sporadic granule conglomerates (Gage, 1952; Ward, 1997). The coal seams in the Eastern Compositional Suite, are thick and numerous as well as multiple carbonaceous mudstone horizons (Ward, 1997; Gage, 1952). The sandstones are normally yellow and can contain sedimentary structures like cross bedding, ripples and channels (Ward, 1997). The Eastern Compositional Suite's sedimentary rocks are generally restricted to the Roa Mine area, where the Rewanui coal seams are being mined.

The Western Compositional Suite consists of very thick and extensive conglomerates that become finer towards the centre of the basin (Gage, 1952, Newman, 1985, Ward, 1997). These conglomerates contain large granitic and hornfels clasts, in addition to the usual Greenland Group and quartz vein clasts. The clasts can reach boulder size in the north-west, where the clasts are always rounded to sub-rounded, with minor imbrication showing a paleo flow direction to the south/south-east (Ward, 1997; Gage, 1952; Newman, 1985). There are also dark, massive mudstone rip up clasts found in multiple areas within the Western Compositional Suite (Ward, 1997). The Western Compositional Suite is its thickest in the north-west where the Rewanui Formations sediments are several hundred meters thick (Gage, 1952). These conglomerates start to fine out into the basin, with a finer grained facies of the Western Compositional Suite, found and seen around Spring Creek and 7 Mile Creek (Ward, 1997).

Ward (1997) put the Cretaceous – Tertiary boundary near the top of the Rewanui Formation at 7 Mile Creek by pollen analysis, giving the formation an approximate age of 65 Ma. The boundary normally occurs just below the last coal horizon in the formation within this area.

The Eastern Compositional Suites depositional environment varies in a meandering environment, with the coal seams known to have been formed from raised mires in a very low energy swamp environment (Ward, 1997; Newman, 1985; Gage, 1952). Therefore, the eastern area would have been low lying with meandering rivers, oxbow lakes and swampy areas (Ward, 1997). However, the Western Compositional Suite was deposited in a higher energy environment, a low angle alluvial fan depositional environment, which is evident by the very thick succession of boulder and cobble clast conglomerate at 12 Mile Beach (Ward, 1997).

3.1.12 Goldlight Formation

Gage (1952) originally mapped the Goldlight Formation describing it as a massive grey to dark grey mudstone. There are sporadic, orange, highly indurated, centimetre thick sideritic concretions found in some areas in the coalfield (Cody, 2015). The most recent revision of this formation has included a non-massive mudstone facies, with normally graded sandstone and minor conglomerate beds, from the north-west as a Goldlight Transitional Member (Ward, 1997; Cody, 2015). Plant and leaf fossils can be located in some areas, as well as mica flakes possibly from a schist source found in the south of the coalfield (Gage, 1952).

The Goldlight Formation is quite continuous as it is present across the entire Greymouth Coalfield, apart from the far north-west, where it laterally grades into its temporal equivalent conglomerates of the Rewanui and Dunollie Formations (Cody, 2015). The thickness of the Goldlight Formation is over 200m in some areas, apart from the north-west, where erosion removed it from the surface and the south-west, where the formation thins out to 50m thick (Newman, 1985; Ward 1952).

The depositional environment that formed the Goldlight Formation was determined to be a lacustrine environment, due to the very fine grainsize, lack of marine fossils and the siderite bands (Gage, 1952; Cody, 2015). The massive, very fine siltstone to mudstone, seen in the eastern part of the basin, is likely formed from hemipelagic sedimentation with little influence from sediment transport processes (Gage, 1952; Ward, 1997; Cody, 2015). The normally graded beds of the Transitional Member are interpreted as turbidites off adjacent deltas (Cody, 2015).

3.1.13 Dunollie Formation

The Dunollie Formation is the most extensive unit. It mainly consists of polymictic conglomerate, yellow sandstone with siltstone and carbonaceous mudstone bedding (Gage, 1952; Ward, 1997; Nunweek, 2001). The formation's coal reserves are underwhelming and not extensive, with common splits in the seams (Gage, 1952). In the north-west of the coalfield the Dunollie is channelized, substantially thick, imbricated conglomerate to the south, with a likely source area to the north and north-west (Ward, 1997; Gage, 1952). The Dunollie conglomerate in the north-west is indistinguishable from the underlying Rewanui conglomerates in the same area. Gage (1952), assigned a thickness of over 200m. At the top of the Dunollie at 12 Mile Beach near the mouth of 10 Mile Creek, the conglomerates are extremely leached and white in colour, which is distinct from the rest of the formation (Gage, 1952; Nunweek, 2001). Slightly inland, the Dunollie grades from a polymictic conglomerate to a quartzose sandstone, at the top of Spring Creek Road. The bedded sandstone is interbedded with siltstone and carbonaceous mudstone beds (Gage, 1952; Newman, 1985; Ward, 1997; Nunweek, 2001).

Denudational processes have eroded most of the Dunollie Formation in the north-east corner of the coalfield, but the formation crops out in the central area around Sewell Peak, Spring Creek and 9 Mile Creek, and in the western area at 10 Mile Creek and 12 Mile Beach (Gage, 1952). The thicknesses vary in these locations from 10's of metres to over 100m thick east of Strongman Mine (Gage, 1952; Nunweek, 2001; Newman, 1985) to over 200m thick at 10 Mile Creek. A drier and/or warmer climate may also have been present, resulting in increased peat oxygenation and weathering of feldspars (Newman et al., 1980). The leaching is thought to represent a significant hiatus between deposition of the tectonically confined Paparoa Coal Measures, and the commencement of a more regional depositional system in the Eocene (Nathan, 1978).

The Dunollie is interpreted as being formed by two fluvial environments, the braided river and deltas in the north-west and meandering rivers and deltas in the east. This is evident due to the presence of conglomerates in the west, and channelized river and delta sandstones, siltstones, mud and coal to the east (Ward, 1997; Gage, 1952).

3.1.14 Brunner Formation

The Brunner Formation overlies the Paparoa Coal Measures and the contact between the Dunollie and Brunner signifies the end of the Paparoa Coal Measures. The Brunner Formation extends well beyond the Greymouth Coalfield with Brunner sediments reported from south of Hokitika to the north into the Nelson region (Nathan, Anderson, Cook, Herzer, Hoskins, Raine, & Smale, 1986). Most Brunner Coal Measures are dated as Middle to Late Eocene, however at Greymouth, a Paleocene aged Brunner has been identified (Nathan, et al., 1986; Nunweek, 2001). The Brunner is generally fine to coarse interbedded quartz sandstone containing micaceous material, but the Palaeocene Brunner Formation is comprised of quartz conglomerate, with minor greywacke clasts, that meets the underlying Greenland Group dominated Dunollie conglomerate, with a sharp erosional contact (Gage, 1952; Newman, 1985).

The Palaeocene Brunner Formation was suggested to define the change between the Dunollie and the Palaeocene aged Brunner Coal Measures, only observed in the Greymouth Coalfield (Gage, 1952; Nunweek, 2001). The Palaeocene Brunner Formation transition is interpreted as an increase in tectonic uplift and subsequent erosion (Newman, 1985; Nunweek, 2001). The Brunner Coal Measures represent the first of the major units associated with the Tertiary marine transgression (Nathan, 1978).

Deposition occurred in a widespread fluvial system bounded by an encroaching marine facies. This formed different basin geometry and coarser sedimentary lithologies, with a different composition to the conglomerate at 12 Mile Beach, which could imply a different source rock (Newman, 1985; Nunweek, 2001).

3.2 Sedimentology of Sample Localities

The facies analysis throughout the Paparoa Coal Measures was developed in previous investigations in the Greymouth Basin (Ward, 1997; Cody & Bassett 2014;

Cody, 2015; Maitra & Bassett 2016). These facies interpretations have been applied to outcrop and the older drill core descriptions, to illustrate the facies evolution.
The 12 Mile Beach section was investigated and measured, with the help of descriptions and interpretations from Mrinmoy Maitra and Emma Cody (Cody & Bassett 2014; Cody, 2015; Maitra & Bassett 2016; Maitra & Bassett, 2017b). A total of five drill cores were investigated, 620, 632, 634, 649 and 660. The depositional facies evolution through each drill hole and outcrop provide a spatial representation of the evolution through time of the Greymouth Basin. This provides the basin geometry and overall picture of what the basin looked like, at different times, throughout its evolution. This will help in determining where the source areas are for the provenance analysis.

3.2.1 12 Mile Beach Section

Due to time and weather, it took multiple trips to complete the measurement of the 12 Mile Beach outcrop. The stratigraphic column of this outcrop shows the majority of the stratigraphic section along the north-west side. However, the entire stratigraphy of the Paparoa Coal Measures does not exist at this location. The Jay, Ford and Goldlight Formations are not present at this outcrop (Gage, 1952; Laird, 1972; Nathan, 1978; Newman, 1985; Newman & Newman, 1998). Instead, the Morgan Formation sits unconformably on the Greenland Group basement, skipping the Jay and Ford Formations. The Goldlight Formation is missing between the Rewanui and Dunollie Formations, which made it more difficult to determine when we reached the contact between the two very similar, boulder to pebble polymictic conglomerates.

The stratigraphic column has been divided into thirds, to allow for the detail to show as the entire column would not have fitted on one page (Figure 3.1, 3.2 and 3.3).

The Morgan Formation deposit is composed of predominantly a medium pebble to cobble, sub-rounded, clast supported, and moderately sorted, polymictic conglomerate at the base. The clasts compositions range from Greenland Group, quartz, aplite and hornfels clasts. The conglomerate is reasonably thick and was determined to be a braided river, due to the overall interbedded nature of the rounded, clast supported conglomerates and the slight imbrication towards the north-east, indicating a paleoflow coming from the north-west towards the north-east. At the top of the formation there are some siltstone and fine sandstone beds, that were interbedded within the conglomerate, that support the interpretation of a braided river depositional setting transitioning into a gravelly delta.

The Waiomo Formation lies stratigraphically on top of the Morgan Formation (Figure 3.3). This formation was observed to consist of alternating mudstone, siltstone and sandstone. The beginning of the Waiomo Formation at this location began with the transition between the Morgan and the Waiomo. This began with sandstones, coal and some conglomerate. Ripples, cross beds and laminated coal of an inter-distributary bay and swamp, in a gravelly delta. The transition into the Waiomo continued up section, with a gravelly delta foresets. This was determined from the reduction in finer sediments, coarsening upwards, into coarser sandstones and conglomerates (e.g. Collinson, 1996; Makaske, Smith, & Berendsen, 2002; Jones & Hajek, 2007; Ahmed, Bhattacharya, Garza, & Li, 2014). The last of the transitional facies into the deep lacustrine deposit is the gravelly delta slope, which was identified by the fluctuations of coarse clastic gravel turbidites, within the finer siltstones and fine sandstones. Soft sediment deformation was observed in multiple locations within this transition. Taken together, these are components of a gravelly delta with gravelly turbidites on the slope (e.g. Türkmen, Aksoy, & Taşgin, 2007; Arnott, 2010; Ahmed et al., 2014). The deep lacustrine deposits of the Waiomo were determined by the thick succession of siltstone and mudstone beds. Evidence of turbidites of coarser sandstone material supports the interpretation as a lacustrine depositional facies (e.g. Turkmen et al., 2007; Arnott, 2010). As the Waiomo Formation transitions into the Rewanui Formation, the opposite sequence of transitional deltaic facies was observed, with gravelly turbidites, a gravelly delta slope and swamp, comprising the depositional facies moving into the Rewanui Formation.

The Rewanui Formation was interpreted as a sub aerial gravelly braided river depositional facies (Figure 3.3). This is evident by deep erosional channels, slight imbrication and the thick deposit of pebble to boulder, polymictic conglomerate with sandstone lenses and beds (e.g. Collinson, 1996; Turkmen et al., 2007).

The Goldlight Formation is not present at this location but is represented by laterally equivalent Rewanui/Dunollie Formations (Figure 3.1, Figure 3.2 & Figure 3.3). It is difficult to distinguish between the two at this location, as both of the formations are composed of similar depositional facies.

The lateral equivalent Rewanui and Dunollie Formation consist of a gravelly delta with pro-grading and retrograding gravelly mouth bars, gravelly delta slopes, and floodplains and swamps (Maitra & Bassett, 2016; Maitra & Bassett, 2017b). The floodplains and swamp depositional setting were determined by the mudstone and siltstone, interbedded with fine sandstone. These beds were observed with ripples, laminated coal and roots. These sediments and structures are typical of floodplains and swampy environments (Collinson, 1996; Makaske et al., 2002; Ahmed et al., 2014). The gravelly delta slope was determined due to the thick sequence of poorly sorted, medium pebble to boulder, polymictic conglomerate with sandstone lenses, with abundant soft sediment load casts and convolute bedding. Imbrication and cross bedding were also observed. The evidence of soft sediment deformation in particular, indicates a sub-aqueous environment with high sediment input in a gravelly delta or fan delta (e.g. Collinson, 1996; Makaske et al., 2002; Jones & Hajek, 2007; Ahmed et al., 2014).

The Dunollie Formation at 12 Mile Beach is dominated by a thick sequence of slightly imbricated, poorly sorted, medium pebble to boulder, polymictic conglomerate, with a few sandstone beds. The top of the Dunollie Formation is severely bleached, requiring soil processes, indicating a sub-aerial depositional environment. This location was interpreted as a braided river depositional environment (Figure 3.1) (Collinson, 1996; Makaske et al., 2002; Turkman et al., 2007; Ahmed et al., 2014). This formation marks the top of the Paparoa Coal Measures.

The 12 Mile Beach location is dominated by coarse conglomerates, suggesting that this location is generally dominated by a high energy depositional environment, relatively close to a source area, due to the size of some of the conglomerate clasts (Figure 3.1, Figure 3.2 & Figure 3.3) (Johnsson & Basu, 1993). The interpretation suggests that the basin evolution at this location began with a braided river depositional environment, which was high in energy. The sedimentation changed as the environment transitioned into a lacustrine dominated one. The lacustrine environment didn't last at this location, as the sediment size increased as the lacustrine environment evolved into a high energy braided river depositional setting. The depositional setting evolved from this high energy braided river environment to a gravelly delta, entering a lake, with fluctuations of low energy environments (inter-distributary bay and swamp), to a higher energy environment (gravelly mouth bar). The fluctuations continued for a long time, until the environment evolved again into a gravelly braided delta/river depositional setting.

The changes in the depositional facies indicate that this location is close to a large sediment source, with some high topography that is interbedded with lacustrine facies. The fluctuations in facies at this location will be due to periods of alternating high and low tectonic activity, which allows for erosion to catch up with topography (Leeder 1999; Gawthorpe & Leeder 2000). The interpretations above support and add detail to previous interpretations of this location (Gage, 1952; Nathan, 1978; Newman, 1985; Newman & Newman, 1992; Ward, 1997; Cody, 2015).

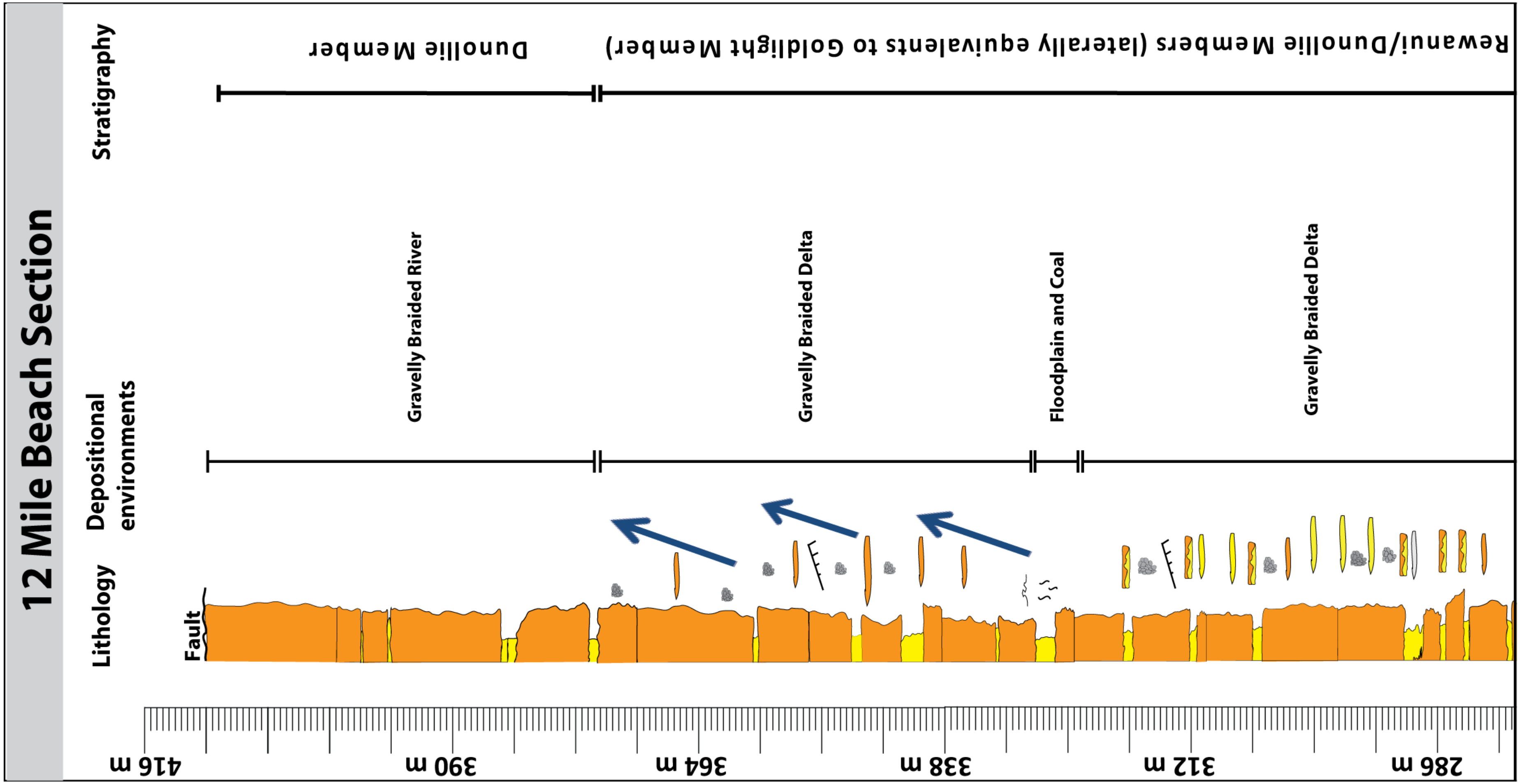

Figure 3.1 12 Mile Beach Stratigraphic Column

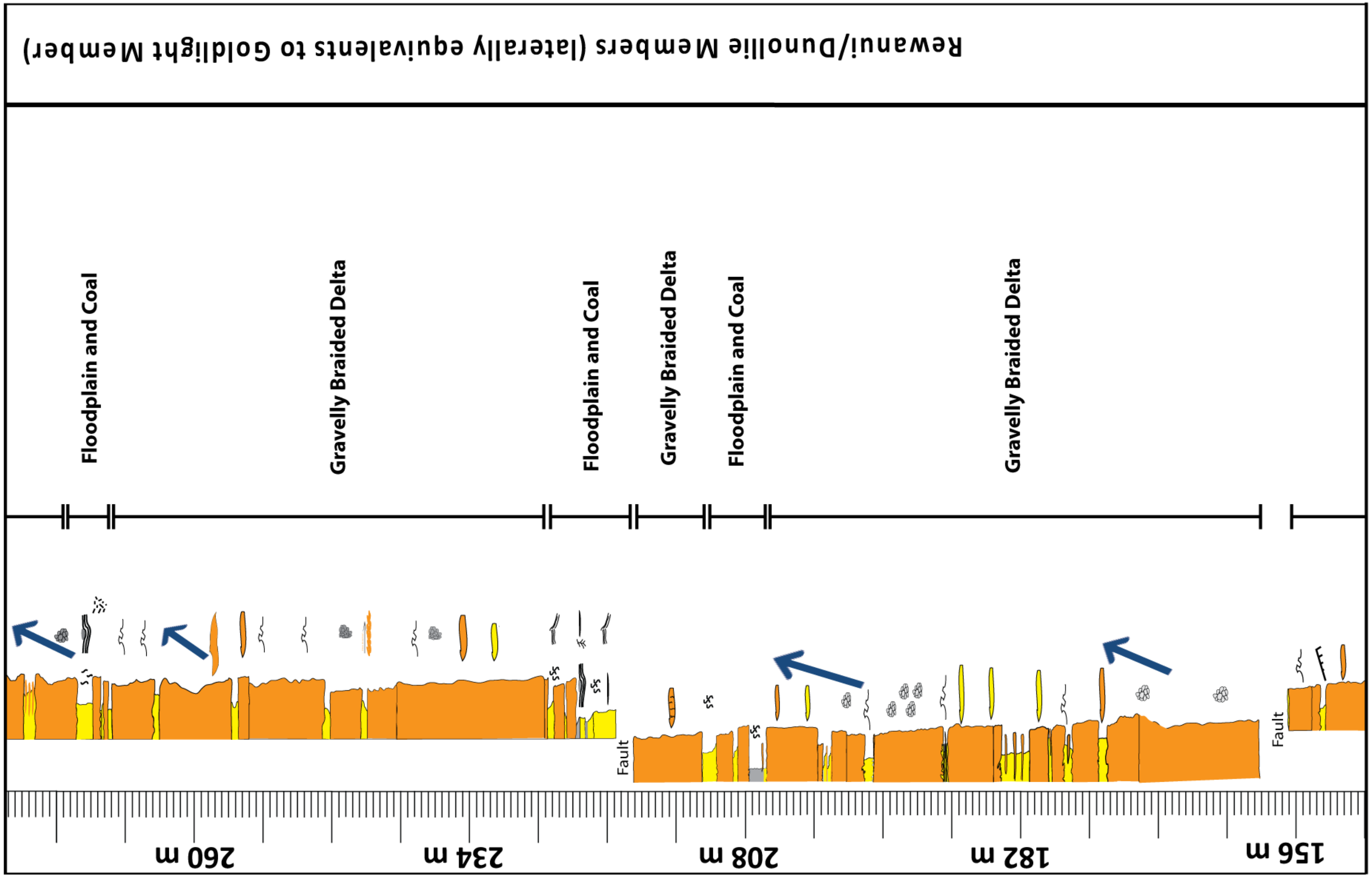

Figure 3.2 12 Mile Beach Stratigraphic Column

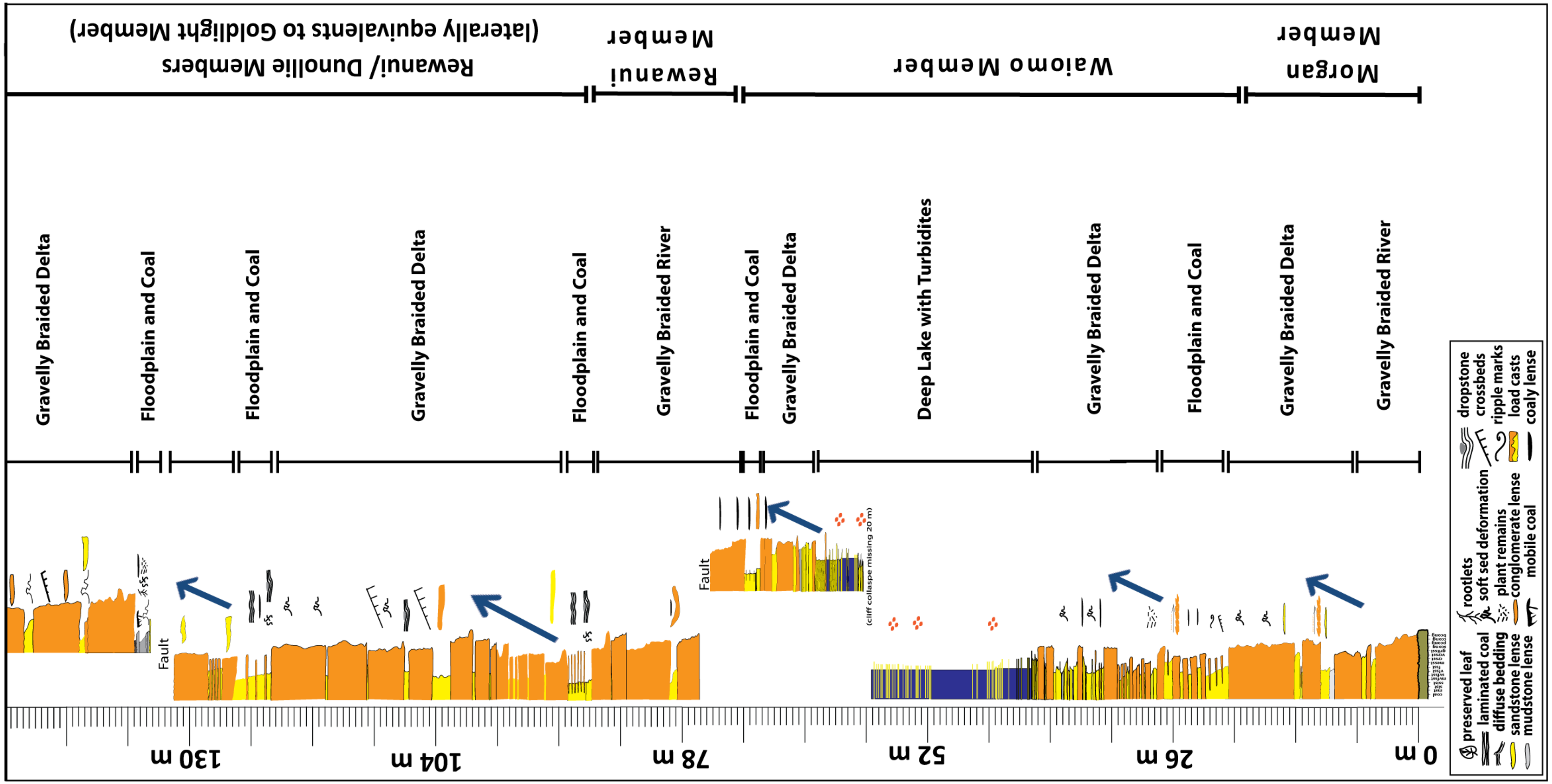

Figure 3.3 12 Mile Beach Stratigraphic Column

3.2.2 Core logs

A total of five different drill cores, spread over the basin were examined; drill holes 620, 632, 634, 649 and 660 (Figure 2.1). These were chosen because of the distribution over the basin, the formations that were intersected and the availability at the core store in Featherston, New Zealand.

The drill cores were divided into four different depositional facies; Lacustrine, braided river/delta, meandering river/delta and floodplain/coal.

3.2.3 DH 634

Drill hole 634 is located in the north-west corner of the basin near 12 Mile Beach (Figure 2.1). This drill hole intercepted only two of the seven Paparoa Coal Measure formations (Figure 3.5). The drill hole terminated in the Rewanui Formation as the drill hole intercepted warm artesian water and gas.

The Rewanui Formation consists of two distinct lithological deposits, 1. Coarse pebble to cobble, clast supported, well rounded, moderately sorted, polymictic conglomeratic material, interbedded with sandstones and 2. Finer sediments, mudstone and siltstone interbedded with varying quality coal and coal lenses. The coarse conglomerate beds are generally substantially thick ranging from 0.3m to 50m thick beds. The interbedded sandstones are usually carbonaceous with a high mud and silt content. The finer mudstones and siltstones, alternate with coal lenses and beds in-between. The mudstones and siltstones are generally massive, poorly sorted, with fine sand and stringers of organic matter. The coal beds ranged from 0.4m to 2.7m thick, of dirty to bright quality coal.

The Rewanui Formation has been divided into two depositional facies. The first depositional setting was determined to be a braided river/delta system, due to the coarse conglomerate material interbedded with sandstones, with an abundance of organic stringers. The second facies within the Rewanui is the floodplain/coal facies which is indicative of the low energy finer sediments, mudstone and siltstone, interbedded with varying ranges of coal quality coal and coal lenses. These pockets of low energy, low sedimentation, will have formed off the sides of the river and delta, alongside the lake.

The Dunollie Formation is extensive at this location with over 300 metres of pebble to cobble, well rounded, moderately sorted, clast supported, polymictic conglomerate, with minor interbedded massive sandstones. This was determined to have been deposited within a high energy, braided river depositional setting, due to the coarse conglomerate sediments and the substantial thickness of the deposit.

The drill hole changes very little in depositional facies up section. The facies ranged from low energy floodplain and coal, to high energy braided rivers. This location is dominated by braided rivers and braided deltas that were interbedded with fine sandstones, siltstones and mudstones. Flood plains and coal were present suggesting there were low swampy areas, perhaps trapped between fan deltas entering the lake.

These facies support the previous interpretations of 12 Mile Beach, that the north-west of the basin was dominated by successions of high energy environments and step topography.

3.2.4 DH 660

Drill hole 660 is located in the north-east corner of the basin (Figure 2.1). This drill hole intercepted all of the Paparoa Coal Measure formations except for the Dunollie Formation before terminating in the Jay Formation (Figure 3.4).

The Jay Formation consists of two depositional facies. A thick 42m, coarse pebble to cobble, poorly sorted, sub-rounded, clast supported, quartzose conglomerate deposit, which lies at the base of the Jay Formation. The top of the formation consisted of 28m of fine carbonaceous, well bedded, mudstones and siltstones, interbedded with fine to medium sandstone and coal.

The base of the Jay formation in drill hole 660 was interpreted to be a braided river or delta environment. The top of the formation was interpreted to have formed in a meandering river or delta environment, with the coal forming alongside the lake or river edge.

The thickest Ford Formation was encountered at this location. It consisted of 150m of bedded, carbonaceous, plant and organic debris rich mudstone, with siltstone and fine sandstone occasionally interbedded. This deposit was interpreted to have been formed within a lacustrine environment.

The Morgan Formation consists of interbedded fine, micaceous, organic rich mudstones and siltstones, fine to medium, quartzose sandstones, and split beds of up to 3.9m of high ash to bright coal. This formation at this location was interpreted to have formed in a meandering river or delta environment, with the coal forming in floodplains along the river or delta.

The Waiomo Formation consists of a 25m thick succession of slightly micaceous, plant and organic rich, massive mudstone. This was interpreted to have formed in a lacustrine environment.

The Rewanui Formation is composed of 109.9m of alternating sequences of; 1. very fine pebble to coarse pebble, clast supported, sub-angular to sub-rounded and polymictic conglomerate, and 2. fine to medium grained, micaceous quartzose sandstone, mudstone, siltstone and beds of up to 2.1m of dirty to bright coal. The formation was divided into two depositional facies. The first was interpreted as a meandering river or delta depositional environment, because of the sharp alternating fine to coarse clastic sediments, and the second, was interpreted as a floodplain and coal depositional environment, with coal forming alongside the rivers and lake edges.

The Goldlight Formation consists of a 72m thick sequence of mudstone and siltstones, which are consistent with a low energy lacustrine depositional environment, with little influence from the shoreline slope or shoreline (Johnsson & Basu 1993; Leeder 1999; Reineck & Singh 2012) (Gage, 1952; Nathan, 1978; Newman, 1985; Ward, 1997; Cody, 2015).

This location is dominated by lacustrine, floodplain, coal and meandering river or deltas. These facies indicated that the north-east of the basin was dominated by low lying fluvial environments with a gradual slope.

3.2.5 DH 632

Drill hole 632 is located in the middle of the basin (Figure 2.1) and intercepted five of the seven formations, in the Paparoa Coal Measures; Morgan, Waiomo, Rewanui, Goldlight and the Dunollie Formation (Figure 3.5).

The drill hole reached basement Greenland Group at 673.1m down and stopped soon after (Figure 3.5). The Morgan Formation lies unconformably on top of the basement rock, deposited as quartzose sandstone beds, minor imbricated, clast supported, well rounded, pebble to cobble, conglomerate, with a ~ 15° dip, carbonaceous mudstone and siltstone, and dirty to bright coal beds. The sharp alternating sediments are indicative of a meandering river/delta environment, with the coal forming off to the sides of the river and delta.

The Waiomo Formation lies stratigraphically on top of the Morgan Formation as a very thick, 92m, silty, bedded and cleaved, carbonaceous mudstone deposit with minor fine sandstone lenses ~5.5 cm. This deposit was determined to have been formed in a lacustrine depositional setting due to grainsize thickness, thin stringers of organic matter and minor coarse grained sediment influx.

The Rewanui Formation at this location is comprised of two different depositional environments. The first is an alternating sequence of pebble to cobble, moderately sorted, well rounded, clast supported polymictic conglomerate, interbedded with siltstone and fine to medium quartzose and micaceous sandstone. The second is dominated by fine carbonaceous mudstone and siltstone with dirty coal beds and lenses.

The first depositional environment was determined to be a meandering delta depositional facies, because of the sharp alternating coarse clastic material and fine siltstone and sandstone sediments, with carbonaceous input. The second is a floodplain and coal depositional environment, which is dominated by fine grained sediments and multiple coal deposits.

The Goldlight Formation consists of a 42m thick, micaceous and carbonaceous mudstone and siltstone deposit, with little coarse clastic input. Beds dip ~10°. This was interpreted as a lacustrine depositional environment.

The last formation intersected by the drill hole was the Dunollie Formation. This consists of a 209m thick deposit of alternating siltstone to quartzose sandstone and coarse grit with organic matter. This deposit was interpreted as a meandering river or delta, due to the alternating low to moderate energy lithologies and the presence of carbonaceous material and the transition out of the lacustrine environment.

This location is predominantly dominated by meandering rivers or deltas, with low to moderate energy environments. Flood plains, coal and lacustrine environment also occurred. These facies support the previous interpretations, that the middle of the basin was dominated by successions of low energy environments and was an area of low topography (Gage, 1952; Nathan, 1978; Newman, 1985; Ward, 1997; Newman & Newman 1998; Ward, 1997; Cody, 2015).

3.2.6 DH 649

Drill hole 649 is located in the south-west corner of the basin (Figure 2.1). This drill hole intercepted only four of the seven Paparoa Coal Measure formations, before contact with basement rock Jay, Rewanui, Goldlight, Dunollie Formations (Figure 3.4).

The Jay Formation sits unconformably on top of the Greenland Group basement rock, at 376.9m. The Jay Formation at this location consists of 0.4m of pale brown/green sub-angular to sub-rounded conglomerate and therefore, was left out of the core stratigraphic column, as there was some debate as to whether it was the

Jay Formation or Greenland Group basement. This was counted as Jay in the clast counts.

The Rewanui Formation at this location consists of 51.6m of interbedded fine, carbonaceous mudstone, siltstone and fine grained sandstone with dirty to bright coal beds. The type of depositional facies determined for this environment was a meandering river or delta. This was due to the sharp alternating sediments with carbonaceous material found in the core, as well as transitioning into the Goldlight lake, with the coal forming beside the lake.

The Goldlight Formation sits stratigraphically on top of the Rewanui Formation and consists of a 57m thick sequence of black carbonaceous mudstone, siltstone and thin stringers of organic material. The Goldlight Formation at this location, has been determined to have been formed in a lacustrine depositional setting.

The Dunollie Formation in this location consists of alternating fine to medium grained, muddy quartzose, sandstone beds, with dark carbonaceous mudstone and siltstone with dirty to bright coal beds, up to 2.7m thick. The Dunollie Formation was interpreted to have been formed in two depositional environments. The first was interpreted to be a meandering river or delta, due to the presence of lacustrine sediments. The second interpreted, was a floodplain and coal environment that formed alongside the rivers and deltas.

This location is dominated by meandering rivers and deltas with flood plains, and coal forming along the edge of the lacustrine environments. The depositional environments at this location indicate a low lying gradual slope into the lacustrine environment on the topographical lows.

3.2.7 DH 620

Drill hole 620 is located in the south-east corner of the basin (Figure 2.1). The 620 drill core was missing the majority of the core at the Core Store in Featherston. Only the basal 30 meters of the core was located. Therefore, the core was interpreted based on the core log summary. The 620 drill hole intercepts all seven of the Paparoa Coal Measure formations; Jay, Ford, Morgan, Waiomo, Rewanui, Goldlight and Dunollie Formations (Figure 3.5).

The Jay Formation lies unconformably on top of the basement Greenland Group, deposited as 5m of very fine pebble to coarse pebble, moderately sorted, clast supported, muddy matrix, sub-angular to sub-rounded, conglomerate. The Jay Formation at this location was interpreted as a braided river or delta environment, with the environment transitioning into the Ford lacustrine environment.

The Ford Formation is dominated by a black carbonaceous, 11.5m thick massive mudstones and siltstones, with organic stringers and very fine sandstone lenses. The formation was interpreted as a lacustrine depositional environment at this location.

The Morgan Formation lies stratigraphically on top of the Ford Formation and is composed of 28.6m of alternating dark, carbonaceous, bedded mudstones, siltstones, fine to medium grained quartzose and organic rich sandstones and dirty high ash coal beds, up to 2.8m thick. The Morgan Formation at this location was interpreted as a meandering river or delta, as the Morgan transitions into the Waiomo lacustrine environment.

The Waiomo Formation is stratigraphically next with a 34 m thick deposit of uniformly massive mudstone and siltstone, with thin organic stringers and scattered plant fossils. This formation at this location has been interpreted as a lacustrine depositional environment.

The Rewanui Formation is composed of 214m of sharp alternating beds of; fine to coarse grained quartzose sandstone, dark, carbonaceous, massive mudstone, siltstone and beds of up to 1m of dirty, high ash to bright coal. This formation was interpreted as a meandering river or delta with floodplain and coal forming alongside the river and lakes.

The Goldight Formation is the thickest mudstone and siltstone deposit in the 620 drill core. The formation is composed of 140m of massive, dark brown grey, mudstone with thin organic stringers scattered throughout. This formation was interpreted as a deep lacustrine deposit.

The Dunollie is the last of the Paparoa Coal measures to be intercepted by the 620 drill hole. The Dunollie Formation at this location consists of 213m of sharply alternating fine-grained carbonaceous mudstone, siltstone and fine to medium grained sandstone with organic input. This formation was interpreted to be deposited by a meandering river or delta environment.

This location is dominated by meandering rivers and deltas, with flood plains and lacustrine depositional environments. This location indicates a low lying gradual slope towards the centre of the basin as a topographical low.

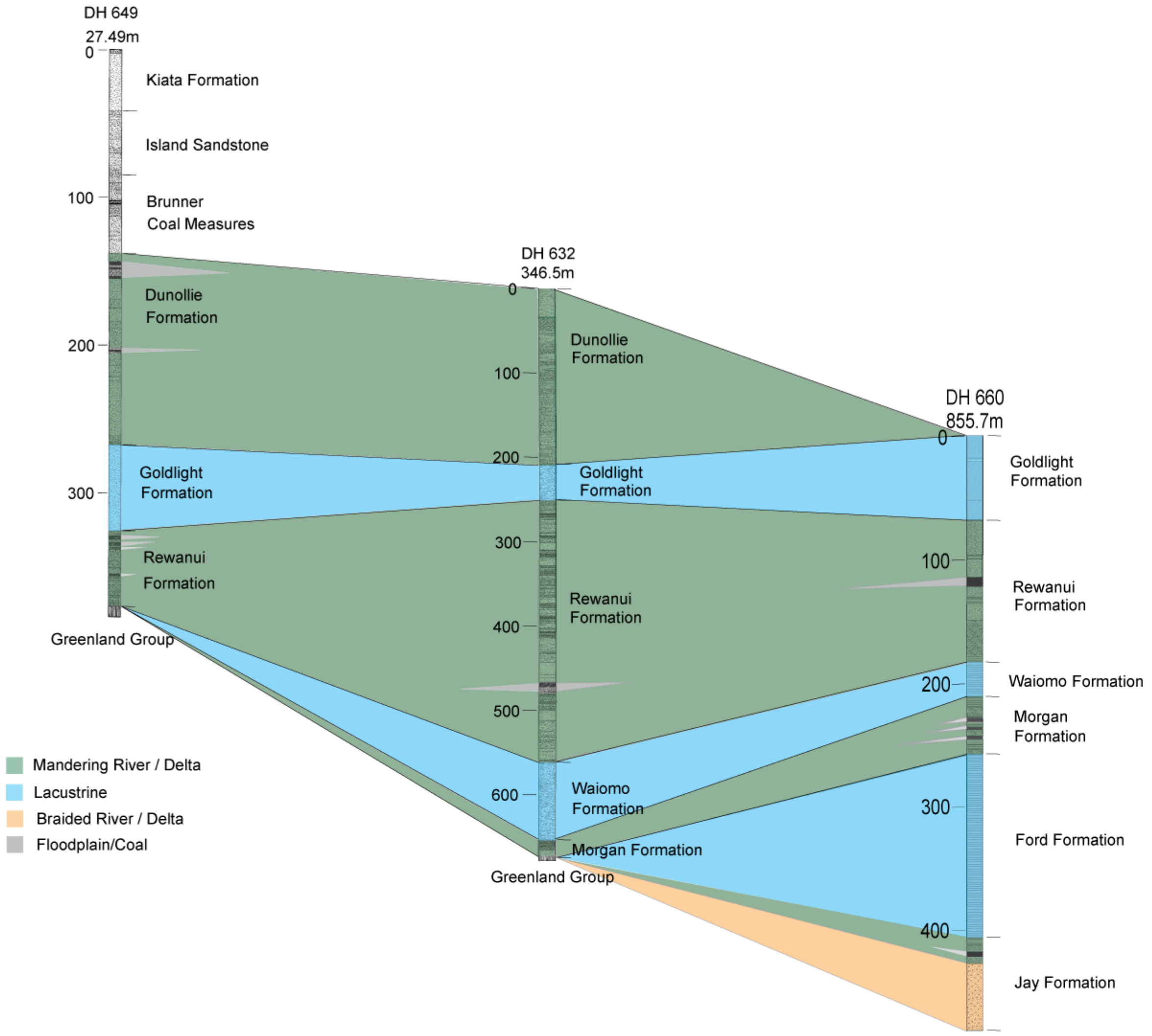

Figure 3.4 Cross section from SW to NE, showing basin facies evolution.

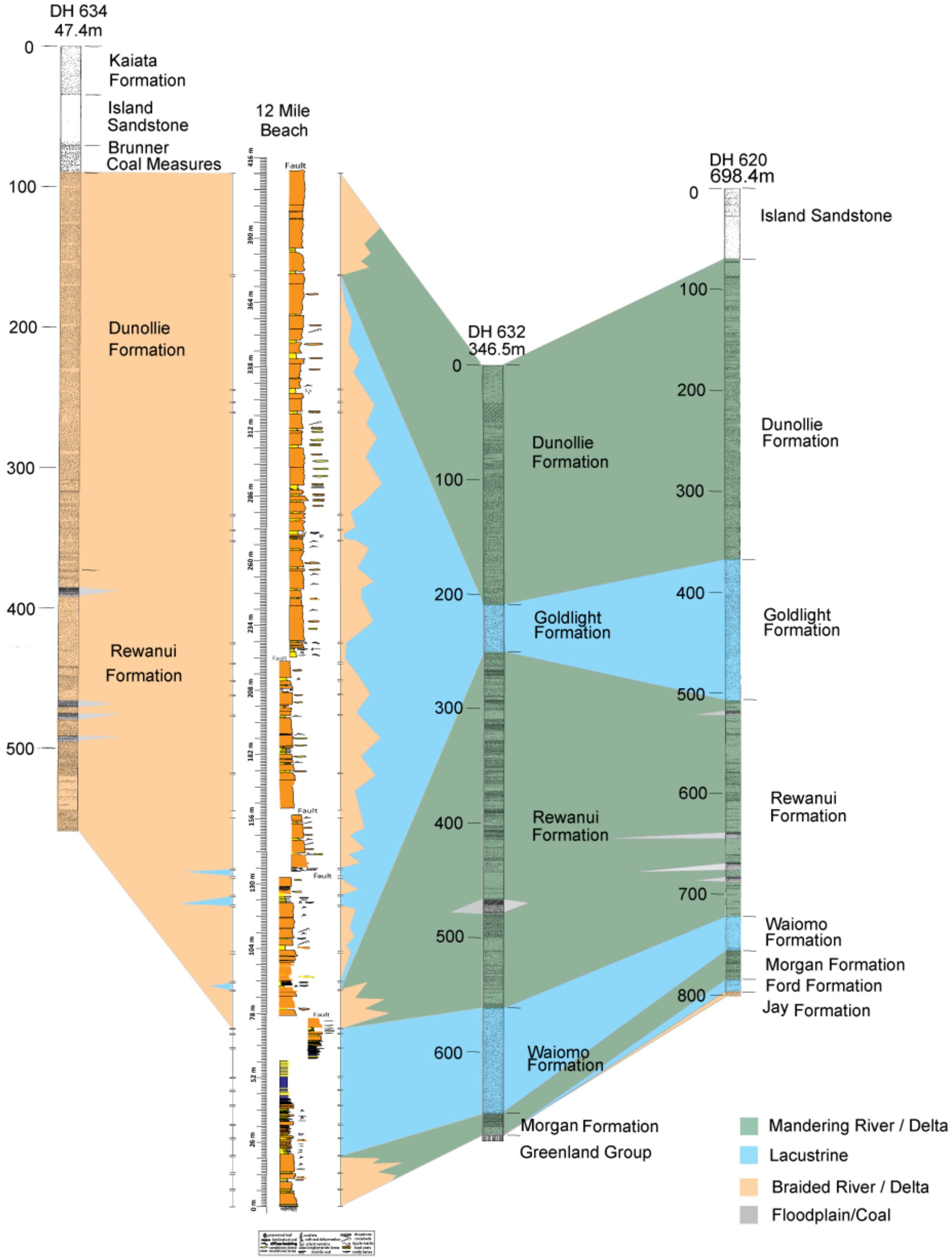

Figure 3.5 Cross section from NW to SE, showing basin facies evolution.

3.3 Stratigraphic Analysis

The depositional facies changes through each drill hole, and outcrop provide a spatial representation of the evolution through time of the Greymouth Basin. This provides the basin geometry and overall picture of what the basin looked like at different times, throughout its history (Figure 3.1, 3.2, 3.3, 3.4 & 3.5).

The cross sections of the drill holes and outcrop show a distinct change in facies across the basin. The 12 Mile Beach outcrop and drill hole 634 in the north-west, are dominated by high energy coarse clastic sediments, deposited in braided river and gravelly delta depositional settings. This indicates an area of steep topography and high relief in the north-west of the basin, and a gravelly braided river and delta prograding and retrograding into the coeval lacustrine deposits in the centre.

Drill holes 649, 632 and 660 represent the centre and axis of the basin. The south-western drill hole 649 shows sharp alternating low to moderate energy environments of meandering rivers and deltas consisting of fluctuations of sediment size and input with periods of lacustrine dominated depositional environments (Figure 3.6 & 3.7). The middle of the basin, drill hole 632, is dominated by the same sequence of depositional facies, fluctuating between meandering deltas and lacustrine deposits. The north-east of the basin, drill hole 660, was dominated by the same alternating depositional environments of meandering rivers and delta facies, lacustrine, floodplain and coal, as drill hole 649 and 632. The thickest and most abundant lacustrine deposits and same sequences of depositional facies across the three drill holes, indicates that they run along the axis of the basin. These drill holes show sharp alternating, low to moderate energy environments of meandering rivers and deltas, during periods were the increased sediment supply overtakes the basin subsidence and accommodation space. During the periods where the basin subsidence is greater than the sediment supply, the lacustrine deposition prevails.

The south-east, shown by drill hole 620, is predominantly dominated by meandering rivers and deltas, with sharp alternating low to high energy environments, flood plains and large periods in time of very low energy deposition are indicative of lacustrine depositional environment. This location is very similar to the depositional settings present in the centre of the basin (Figure 3.6 & 3.7).

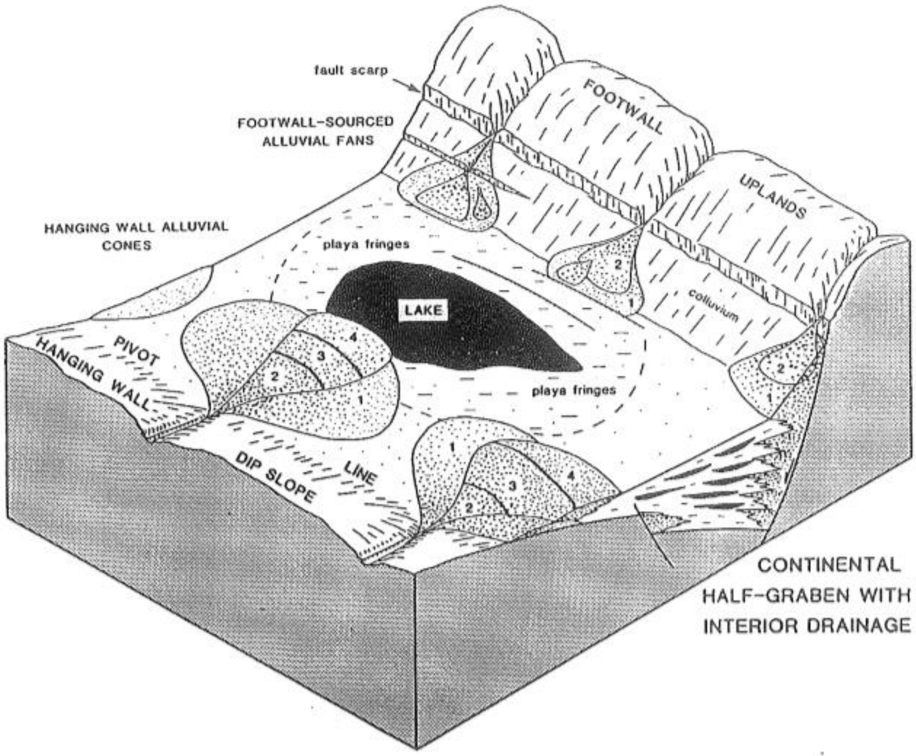

Figure 3.6 Showing Leeder & Gawthorpe (1987) interpretation of paleo environment of a Rift Basin.

The facies distribution and evolution through time are consistent with rift basin geometry (Figure 3.6 & 3.7) (Leeder & Gawthorpe 1987; Gawthorpe & Leeder 2000). The spatial distribution of depositional environments is primarily controlled by the structural asymmetry of the rift basin (Leeder & Gawthorpe 1987; Gawthorpe & Leeder 2000). The formation of a half graben commonly results in an asymmetrical basin where the faulted foot-wall margin is steeper, and produces higher energy facies than the un-faulted hanging-wall hinge side (Figure 3.6 & 3.7). Due to the change in slope angle, rapid deposition occurs at the base of the footwall. This has a major impact on deposition and facies distribution across the basin (Leeder & Gawthorpe 1987; Gawthorpe & Leeder 2000). Changes in facies within the centre of the basin are primarily controlled by the subsidence rate of the basin, caused by the extensional regime (Leeder & Gawthorpe 1987; Gawthorpe & Leeder 2000). Accommodation space is created by the amount of subsidence and therefore, when the subsidence is greater than the sediment supply, the lacustrine depositional environments form (Figure 3.6) (Leeder & Gawthorpe 1987; Gawthorpe & Leeder

2000). When the sediment supply is greater than the subsidence rate, the meandering rivers, swamps and floodplains prevail (Figure 3.7) (Leeder & Gawthorpe 1987; Gawthorpe & Leeder 2000).

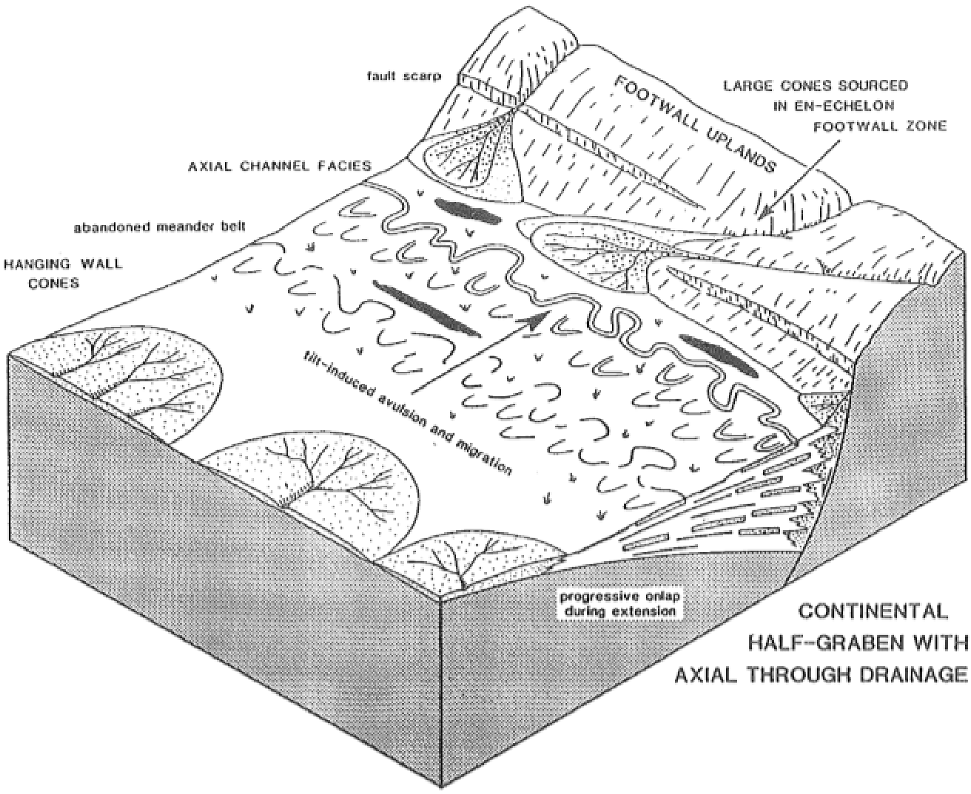

Figure 3.7 Showing Leeder & Gawthorpe (1987) interpretation of paleo environment of a Rift Basin.

The location, lithologies and depositional facies of the deposits across the basin allow for a paleo reconstruction of the geometry of the Greymouth Basin. The coarse clastic sediments are restricted to the north-western corner of the basin. This indicates that the boundary and highlands are to the north-western corner of the basin (12 Mile Beach and DH634) (Figure 3.6 & 3.7). The middle of the basin (DH 660, DH 632 and DH 649) was dominated by lacustrine alternating with meandering river facies, indicating axis of the basin running parallel to the boundary fault. The south-eastern side of the basin (DH 620) is dominated by meandering river and lacustrine deposits, indicating the hinge with a gradual sloping topography towards the centre of the basin. However, due to the depositional facies present at the drill hole 620 location, the interpretation of the hinge is sceptical, as it closely resembles the centre of the basin.

The typical half graben tectonic setting illustrated by the terrestrial sequence of lacustrine, and meandering and braided facies indicates there were four dominant source areas with influence from axial drainage from the south-west and north-east. The up thrown highlands to the north-west (12 Mile Beach and DH 634) are dominated by the higher energy braided river/delta depositional facies (Figure 3.6), suggesting that the conglomerates source area is to the north-west. The gradual sloping topography towards the basins centre from the south-east (DH 620), indicates the hinge lowlands of the half graben (Figure 3.6). This signifies the second source area for the finer clastic sediments, lies to the south-east. The low gradual slope towards the centre of the basin in the north-east (DH 660) and south-west (DH 649), indicate two axial drainage rivers and sediment entrances.

Chapter 4 Provenance Analysis

Field observations were used to determine composition, structures and textures in hand samples. While clast counts were implemented for the conglomerate lithologies. Clast counting illustrates the assemblage of the constituent's rocks within the whole rock in a particular area. These techniques provide information on the number of source rocks, and from the size of clast, we can imply the distance to the source. For example, the predominance of a single clast type usually represents a single source rock for the sediments, and generally small, local drainage system (Horton, 1998; Johnsson & Basu, 1993; Arribas et al., 2007; Reineck & Singh, 2012). Conglomerates, where more than one clast type is present, indicates multiple different source rocks and possibly a large inclusive drainage network (Horton, 1998; Johnsson & Basu, 1993; Arribas et al., 2007; Reineck & Singh, 2012).

Petrographic analysis will be undertaken, using microscopes to determine the composition of sand grains by point counting (Arribas et al., 2007). Point counting is a statistical technique similar to clast counting, but it focuses on the individual grains comprising the sandstone. It involves looking at a large number of points (grains of sand) on the slide, recording exactly what is seen at each point and then assembling a description from all the information recorded. In order to be a statistically valid representation, the number of points described is typically 300 – 500.

4.1 Conglomerate Provenance

Conglomerates from 12 Mile Beach and drill hole core 620, 632, 634, 649 and 660 were counted across the basin (Figure 2.1). Clast counts were taken at every intercepted conglomerate in all the coarse clastic formations (Jay, Morgan, Rewanui and Dunollie). The initial clast counts resulted in 11 different clast types and samples. The clasts found were; green and brown metasandstone, hornfels, quartz, granite, green argillite, aplite, mudstone, basalt, white brecciated clast, and the conglomerate clast. These clasts ranged in size (from fine pebble to boulder), and rounding (sub-angular to rounded). Details of hand samples, thin sections, core, and outcrop descriptions of the clasts types encountered are described below:

Green and Brown Metasandstone Clasts

The green and brown metasandstone clasts vary in size from fine pebble to boulder, very well indurated, sub to well-rounded and vary from silty very fine sand to medium grained sandstone. These clasts were observed in every conglomerate clast count in outcrop and drill core.

Thin sections show very fine-grained metasiltstone to metasandstone with a slight fabric; sub-rounded to rounded, and very well sorted. Composition varied slightly throughout samples with the percentage of the minerals changing marginally with each sample. Components consisted of quartz ~40%, ~10-20% feldspar, muscovite ~1-3%, chlorite ~3-5% and very fine indistinguishable matrix ~ 32-46%. Some minor iron staining was observed in a few of the samples.

These clasts are Greenland Group basement rock, and one of the suspected source rocks for the Paparoa Coal Measures. The Greenland Group is the defined basement rock for the West Coast of New Zealand. It is very distinctive, and as its name suggests, it is a green meta-sedimentary rock (Laird, 1972; Laird, 1974; Nathan, 1978). However, Greenland Group does not always have this distinctive green colour, and can be brownish in appearance. Every conglomerate formation in the Paparoa Coal Measures has a component of these basement rock clasts within it. It is brown to green, highly indurated sandstone and mudstone greywacke, and argillite (Laird, 1972; Laird, 1974; Nathan, 1978). Petrographic analysis shows an abundance of quartz relative to feldspar in the clastic constituents (Laird, 1972; Laird, 1974).

Argillite Clasts

This clast was observed only along the 12 Mile Beach outcrop, as a well indurated mud like clast that appeared green. Laminations can be seen in hand sample and appeared in the Rewanui and Dunollie Formations. The clasts were fine to medium pebble size and sub-rounded (Laird, 1972; Laird, 1974; Nathan, 1978).

There were a few of these clasts that were softer and able to be scratched with a rock hammer at outcrop. This is determined to be due to weathering, as the outcrop was in a highly moist environment being on the beach. Therefore, the normally highly indurated argillite comprised of primarily clay particles would become less indurated with weathering.

These clasts were grouped with the Greenland Group in the collated clast counts, as the Greenland Group also consists of argillite, and they were distinctively green (Laird, 1972; Laird, 1974; Nathan, 1978).

Conglomerate Clasts

This clast type was only observed a couple of times in drill hole 634, at a depth of 480.2m to 488.8m in the Rewanui Formation. This clast appeared as brown to green, speckled, sub-rounded, medium pebble, fine sandstone. These speckles appeared to be granules of lithics, (small clasts of other lithologies) within the sandstone.

Thin section investigation revealed that these specks thought to be lithics were just large grains of quartz. The clast comprised of primarily fine quartz grains ~40% with some large quartz crystals ~10%, a few chlorite crystals<1% and a very fine matrix of feldspar and quartz ~ 49% (Figure 4.8).

These clasts have been determined to be coarser Greenland Group sandstone as composition is very similar to previous Greenland Group clasts, except these are a little bit coarser grained (Laird, 1972; Laird, 1974; Nathan, 1978).

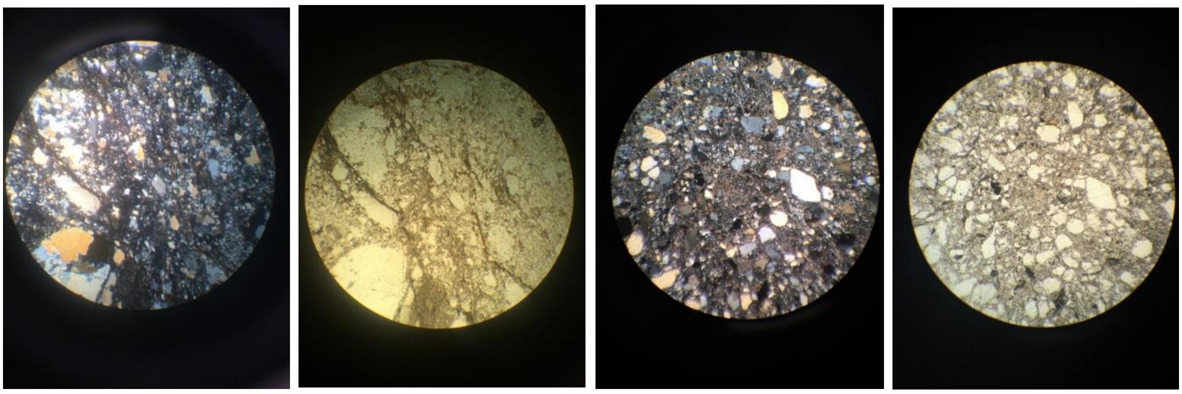

Figure 4.1 Coarse Greenland Group sandstone thin sections in plain and cross polarised light, from sample 6 in the Rewanui Formation, and 24 in the Dunollie Formation from drill hole 634 at 488.5m and 488.65m (from left to right).

Hornfels Clasts

These hornfels facies metamorphic rocks do not appear in the Jay conglomerate but in the Morgan through to the Dunollie Formation, with varying degrees. The clasts range from medium pebble to cobble size; sub-rounded and have an obvious spotted texture (Figure 4.1).

These rocks in thin section have a slight foliation, porphyroblasts, poikiloblast and a very fine to medium groundmass. The spotted mineral was determined as cordierite and not andalusite due to the following; no carbon cross was observed in the spotted mineral in any of the samples, the mineral was not euhedral and no yellow pleochroism, which is somewhat common for the mineral (Figure 4.2). (Phillips & Griffin, 1981; Deer, Howie, & Zussman, 1992). However, cordierite is another common hornfels mineral and usually appears in poorly lineated metamorphic rocks, as irregular porphyroblastic clots (Figure 4.2). (Phillips & Griffin, 1981; Deer et al., 1992). Cordierite also alters rather quickly to a fine-grained, greenish aggregate of largely chlorite, muscovite or biotite, which is commonly known as pinite (Phillips, & Griffin, 1981; Deer et al 1992). The spotted mineral ~ 7% in the hornfels clasts found was an amalgamation of small anhedral low order crystals, with a yellow to green chlorite alteration halo/ring surrounding the mineral (Figure 4.2). The green pleochroic alteration ring has a speckled, slightly purplish colour in cross polarised light (Figure 4.2).The ground mass is too fine to determine but appears to be made of microlites. This mineral meets all the criteria for cordierite, and the green alteration ring is also most likely pinite (Figure 4.2).

Figure 4.2 Hornfels clasts from 12 Mile Beach outcrop and in drill hole core 634 core from within the Rewanui Formation. Core is from 460.5m.

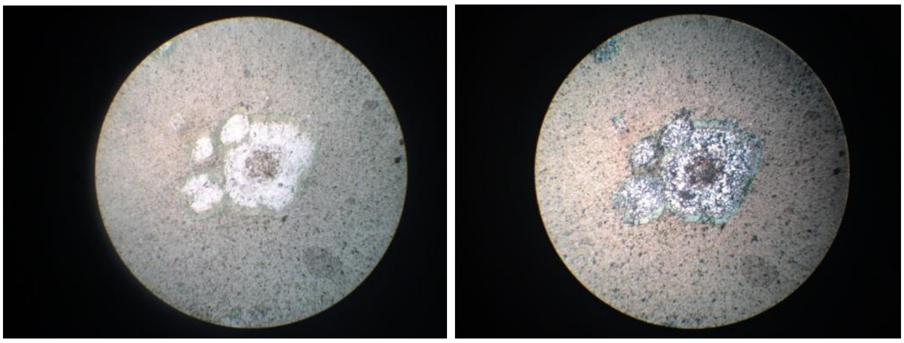

Figure 4.3 Cordierite, sample 12MB04 from 12 Mile Beach, Rewanui Formation, in plain polarised and cross polarised light.

These hornfels clasts are likely Greenland Group that has been metamorphosed by contact metamorphism (Gage,1952; Newman, 1985). This is likely a result of a possible unroofing of a granitic pluton.

Vein Quartz and Clasts

Clear to milky white quartz is common through the majority of the Paparoa Coal Measures. The quartz appeared as large crystalline, fine granule, fragments of vein quartz to coarse pebbles. These were angular to sub-angular clasts, some with a glassy appearance. These clasts were fragments of quartz veins, as the clasts were coarse grained and crystalline.

The source of these quartz clasts is most likely the Greenland Group. The Greenland Group basement has extensive quartz veins throughout the rock (Gage, 1952; Laird 1972; Laird 1974).

Granite Clasts

The granite clasts first appear in the Rewanui Formation and continue up section, up into the Dunollie Formations on the western side of the basin. No granitic clasts were observed in the eastern conglomerates. The clasts range in colour from a slight pink to a grey white across outcrop and core samples (Figure 4.3). The clasts appeared as medium pebbles to boulder, sub-rounded clasts. Some clasts were weathered significantly in outcrop and core, with some quite friable. The clasts exhibited a granitic texture with some having a few slightly larger pink alkali feldspar crystals. Composition in hand samples varied slightly, with approximately 55% quartz, 30% feldspar, 10% muscovite and 5% biotite.

Thin section analysis of the granites both from core and outcrop show some significant chemical alteration of feldspars to clay, with some samples showing very little remaining feldspar crystals at all. The thin sections show typical textures; anhedral, medium to coarse grained, straight and undulatory extinction, granitic, phaneritic and equigranular. Chemical alteration of feldspars was evident with embayments, sericite and complete alteration of feldspar grains. Samples had a range of weathering from minor to major, but all had similar compositions of quartz ~44- 64%, muscovite ~5-10%, plagioclase (polysynthetic twinning) ~ 10-15% alkali feldspar (simple and microcline twinning) ~10 -25%, some opaques and sericite >1%. A few samples had biotite present but in very small quantities ~1-5%.

Figure 4.4 Granite clasts at 12 Mile Beach outcrop, and in drill hole 634 core from the Rewanui Formation. Core from 485.6m

The granitic clasts are thought to come from one of two sources. The Karamea Suite or the Rahu Suite. This is because of the ages being older or of similar age to the Greymouth Basin, and the proximity and prevalence of the granitic bodies. The Karamea Suite is 370 ± 5 Ma and composed predominantly of biotite and/or muscovite granites and granodiorites (Grindley 1961; Tulloch. 1983; Muir et al., 1994; Muir, Weaver, Bradshaw, Eby, Evans, & Ireland,1996). The closest representative of the Karamea Suite to the Greymouth Basin is the Barrytown granite (Nathan et al., 2002). The Barrytown granite is a biotite granite with ~32% quartz, 28.4% alkali feldspar, 28% plagioclase feldspar, 10.9 % biotite, with minor muscovite, apatite and zircon making up the remainder (Tulloch, 1973). The Karamea Suite generally consists of large, pink, prismatic alkali-feldspar megacrysts (30-40 mm in length) in a groundmass of quartz, oligoclase, microcline, biotite, and muscovite with accessory apatite, zircon and iron oxide (Muir et al 1996). However, white alkali feldspar or plagioclase phenocrysts are also common (Muir et al., 1996). The megacrysts often show a strong preferred orientation, because of magmatic flow (Muir et al., 1996).

The 120 -110 Ma (Muir et al., 1994) Rahu Suite is similar to the Karamea Suite. The closest representative of the Rahu Suite is the Buckland granite (Nathan et al., 2002). The Buckland granite is white, medium-grained, weakly foliated biotite-muscovite granite (Adams & Nathan, 1978; Tulloch, 1983; Graham &White, 1990). The Rahu Suite and Buckland granite can typically be distinguished by its white colour, rather than grey or pink, and the abundance of muscovite relative to biotite (Graham &White, 1990). The foliation is considered to be a primary feature because it is defined by an alignment of primary minerals, particularly biotite and muscovite, but also elongate quartz and feldspar crystals (Graham &White, 1990).

The Barrytown and Buckland granites are both similar in hand sample, with comparable compositions, but with some different colour variation. The Buckland however, has relatively more muscovite that the Barrytown. The granitic clasts collected were more abundant in muscovite than biotite, suggesting a possible Buckland granite provenance. However, further geochemical analysis has been completed to determine the source of these granitic clasts more confidently.

Aplite Clasts

Aplite clasts appear in the bottom two formations the Jay and Morgan, increasing in the Morgan up section with the odd occurrence in the bottom of the Rewanui Formation. These white clasts appear in size from fine pebble to cobble, sub-rounded to rounded, and were very hard when struck with a rock hammer. Initially these clasts were thought to be a very well indurated, very fine-grained sandstone but thin sections showed this to be incorrect.

Thin sections show a very fine-grained groundmass with some euhedral quartz, weathered feldspars with sericite and muscovite scattered sporadically throughout the thin sections (Figure 4.4). A few quartz veins also run through the rock in one of the thin sections. The constituents vary slightly from sample to sample, but are predominantly the same with quartz ~ 5%, alkali feldspar- simple twinning ~3%, muscovite ~2%, sericite >1% and groundmass ~90% most likely comprised of quartz and feldspar.

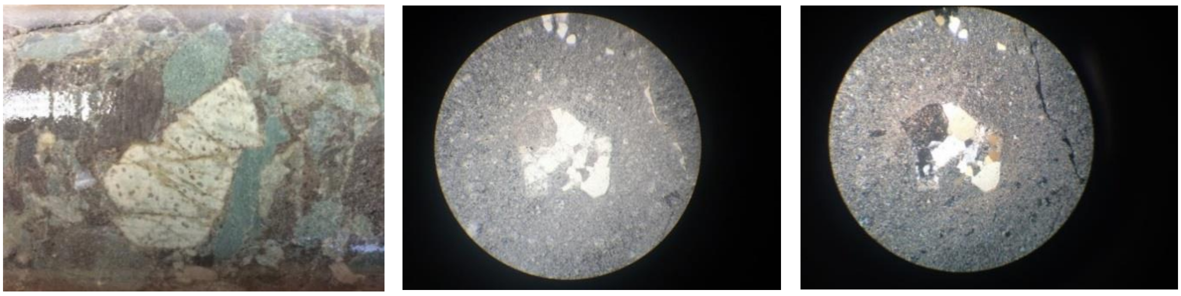

Figure 4.5 Aplite clast from drill hole 660 in the Jay Formation at 470m and aplite sample 12MA04 from 42°19’02.7S 117°16’33.3E, in thin section plain polarised and cross polarised light.

These aplite clasts appear only in the older coarse clastic sediments of the Jay and Morgan Formations. The increasing concentrations of these clasts up section infer that the source of these clasts was becoming more prevalent (Johnsson & Basu 1993). This lithology is the precursor to a granitic pluton being unroofed. This theory is supported with the sudden appearance of coarse granitic clasts in the Rewanui and Dunollie Formations.

White Breccia Clast

This clast was only observed once in the drill hole 634 at a depth of 380.6m to 385.1m in the Rewanui Formation. This clast was white, sub-rounded to round and cobble sized. This clast contained small brecciated fragments of Greenland Group that were granule to fine pebble, sub-rounded to angular and contained in a quartz cement (Figure 4.5).

Thin section analysis showed remnants of feldspars which had weathered away. The quartz cement was sharp, almost radial in sharpish laths, making up ~65% of the composition (Figure 4.5). The rest of the composition was ~10% muscovite, ~10% biotite, ~5% weathered feldspars and ~10% Greenland Group lithic (Figure 4.5). It consists mainly of quartz with muscovite laths, feldspar, biotite and Greenland Group angular clasts.

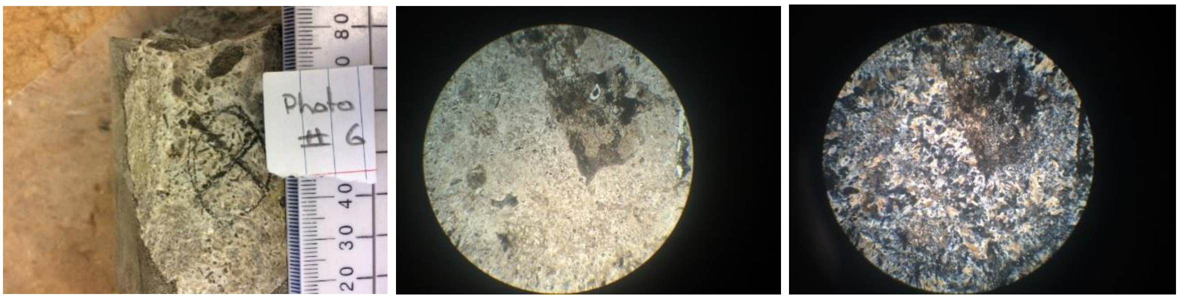

Figure 4.6 White brecciated clast from drill hole 634, Rewanui Formation, from 557.2m, sample 4 thin section in plain polarised and cross polarised light.

This clast is thought to be a pegmatite intruding the Greenland Group (Laird 1972; Laird 1974; Nathan, 1978). This clast is rich in quartz and feldspar with large crystals in thin section (Figure 4.5). The Greenland has multiple quartz veins and pegmatites of coarse quartz and feldspar intruding the basement lithology (Laird 1972; Laird 1974; Nathan, 1978).

Mudstone Intra-clasts

Mudstone clasts were found to be present in the Jay, Rewanui and Dunollie Formations sporadically, as dark to light brown, sub-rounded with strong bedding, fine to coarse pebbles. These clasts were observed in drill core 620 in the Jay Formation, and in a few instances, in drill core 634, in the Rewanui Formation. At the

12 Mile Beach outcrop, the gradational contact between the Waiomo Formation and the Rewanui Formation had multiple mudstone rip up clasts within the base of the Rewanui. The mudstone clasts were often deformed and squished, indicating that these were unlithified at the time of deposition.

Thin sections showed bedding in the samples with some quartz >1% grains, scattered throughout the thin section, comprised primarily of mud and clay with carbonaceous material of ~10% (Figure 4.5).

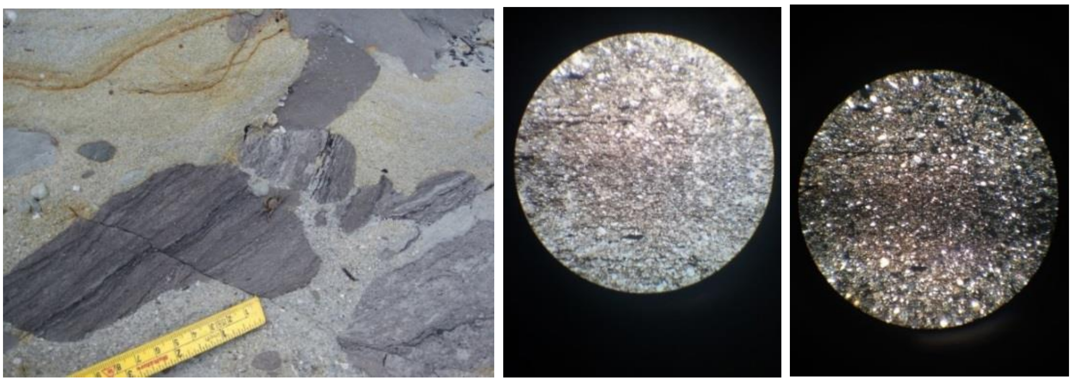

Figure 4.7 Mudstone clasts in the Rewanui Formation outcrop, 42°19’19.41S 171°16’13.15 and thin section sample 12MC01, in the Rewanui Formation from 42°19’19.41S 171°16’13.15 in plain polarised and cross polarised light.

These mudstone clasts came from one of the three lacustrine formations (Ford, Waiomo and Goldlight) (Cody, 2015). The specific formation would be dependent upon the stratigraphic position of the clast.

Basalt Clasts

These dark hard clasts have been observed in multiple locations in outcrop (Rewanui and Dunollie Formation) and in the drill cores (Jay, Morgan and Rewanui). However, after thin section and XRF analysis, these dark clasts thought to be basalt were not all basalts (Figure 4.7). In fact, there were only a few samples of these dark clasts that could be basalts. The majority of these dark clasts were Hornfels of an argillite grainsize, or a slightly more metamorphosed Greenland Group argillite clast.

This intermediate metamorphic rock is comprised of primarily quartz ~74%, biotite ~25% and chlorite ~1%. Biotite and chlorite laths seemed to be orientated in a slight fabric with interlocking quartz crystals (Figure 4.7). There were a few opaques within the sample <1%. The clasts were located in the Rewanui and Dunollie Formation portions of the 12 Mile Beach outcrop.

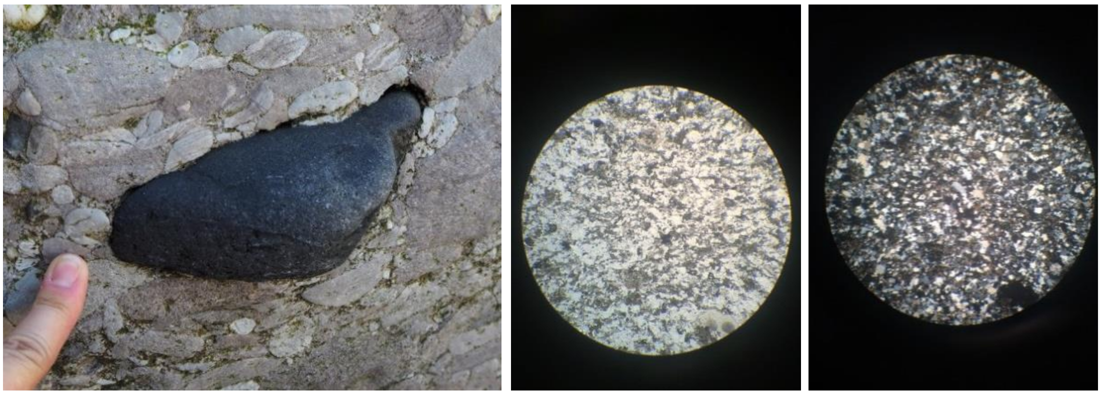

Figure 4.8 Suspected basalt clast from 12 Mile Beach in the Rewanui Formation 42°19'19'43S 171°16'13.27E outcrop and thin section sample 12MB07, plain polarised and cross polarised light.

The dark clasts that turned out to be hornfels had similar compositions and textures as the previous hornfel clasts. These clasts were not identified in hand sample or outcroph due to the lack of a spotted appearance and a few of these clasts appeared to have vesicles. These vesicles however, have been determined to be weathered cordierite spots in hand sample. The clasts in thin section had a slight fabric, fine grained groundmass and irregular porphyroblastic clots. Cordierite ~ 7% in the hornfels clasts was found as an amalgamation of small anhedral low order crystals, with a yellow to green chlorite alteration halo/ring surrounding the mineral. The cordierite in these clasts also had the green pleochroic alteration ring with microlites as the ground mass.

The five clasts that could possibly be basalt, samples 5, 8, 9, 12MB01 and 12MC04, rely on the geochemistry for identification as no thin sections were available.

4.1.1 Clast Counts

Clast counts were taken from outcrop (12 Mile Beach) and cores (620, 632, 634, 649 and 660) from across the basin (Figure 2.1). The data combined core and outcrop counts will be presented in terms of the formations.

The clast count from the Jay Formation in drill hole 649 has been attributed to the Jay Formation following the drill hole summary of the core. However, this sample could also be attributed to the Morgan Formation.

The combined Jay Formation counts only include core counts as the Jay Formation was not encountered at the 12 Mile Beach outcrop.

The Jay Formation is dominated by Greenland Group sourced clasts and quartz (Figure 4.9). Drill hole 620 has a mudstone influence with over 20% of the conglomerate composed of mudstone clasts. Drill hole 660 has some aplite and minor basalt influence (Figure 4.9). This is likely due to the drill hole location being close to the Morgan Volcanics located in the north-east.

The Morgan Formation was mainly intercepted at 12 Mile Beach. It was dominated by Greenland Group clasts and quartz with an increase in aplite up section (Figure 4.10). The hornfels component was reasonably consistent with the exception of drill hole 620.

The Rewanui Formation clast counts show that Greenland group is still the dominant clast type. The first clast count (42°19’19.41 S 171°16’13.15 E) at 12 Mile Beach, shows a gradational contact between the Waiomo and Rewanui Formation (Figure 4.11). This is evident by the large amount of mudstone clasts within the conglomerate at this location. Granite clasts seem to fade out laterally across the basin (Figure 4.11). Aplite also seems to fade out completely at the beginning of the formation (Figure 4.11).

Dunollie is dominated by the Greenland Group and quartz with the only other influence coming from hornfels and granite (Figure 4.12). The granite percentage appears to be highest at 12 Mile Beach than at drill hole 634 (Figure 4.12).

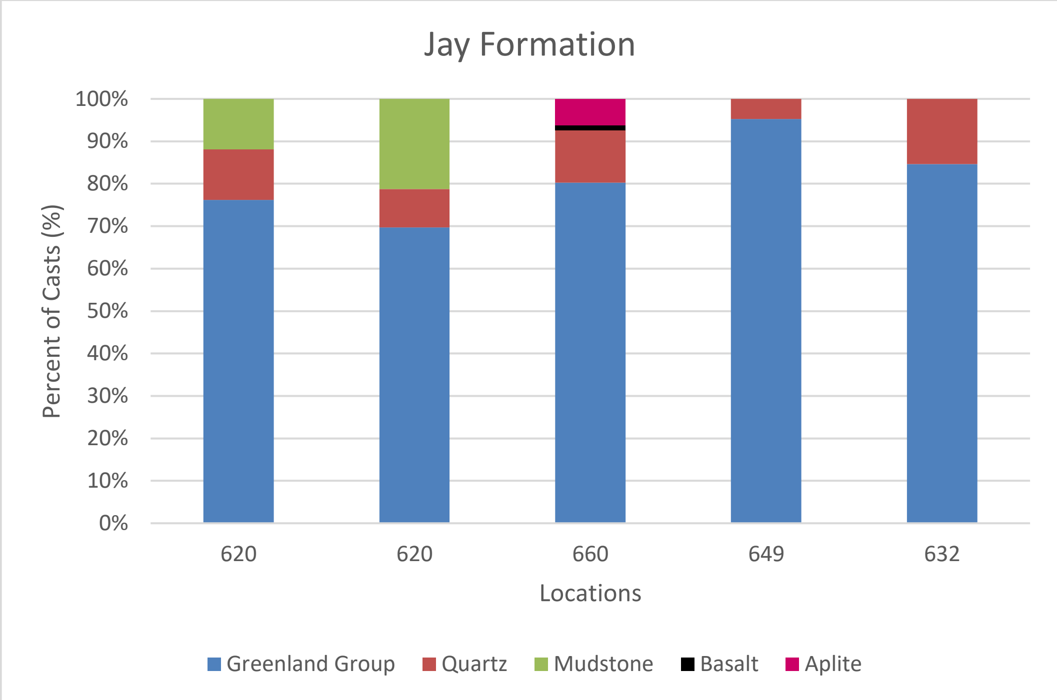

Figure 4.9 Clast counts for the Jay Formation.

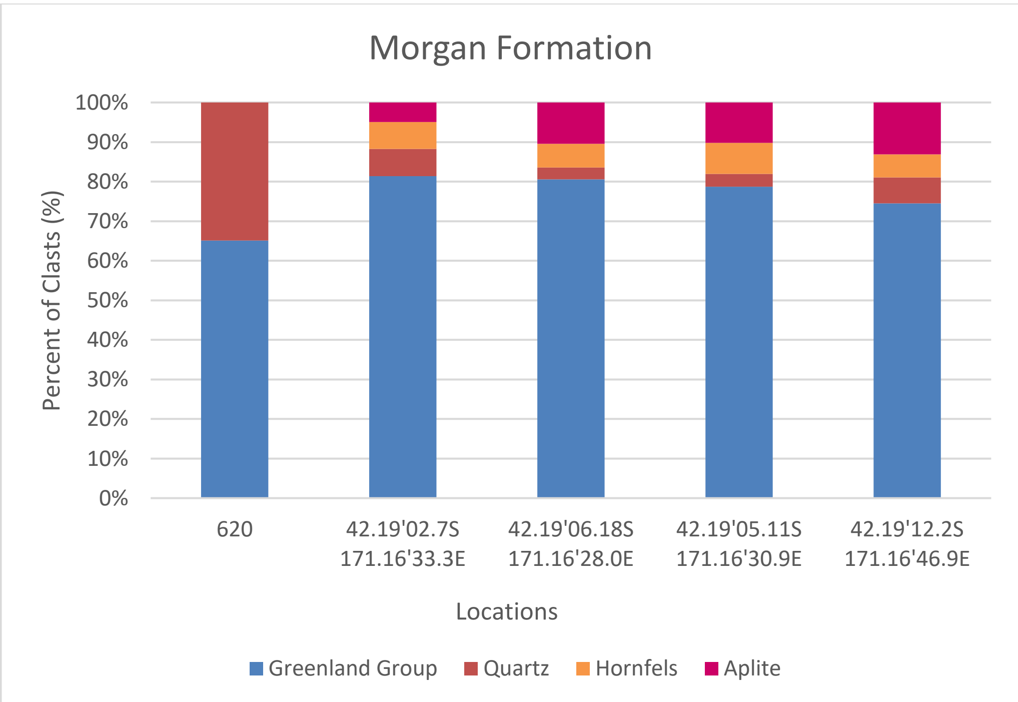

Figure 4.10 Clast counts for the Morgan Formation.

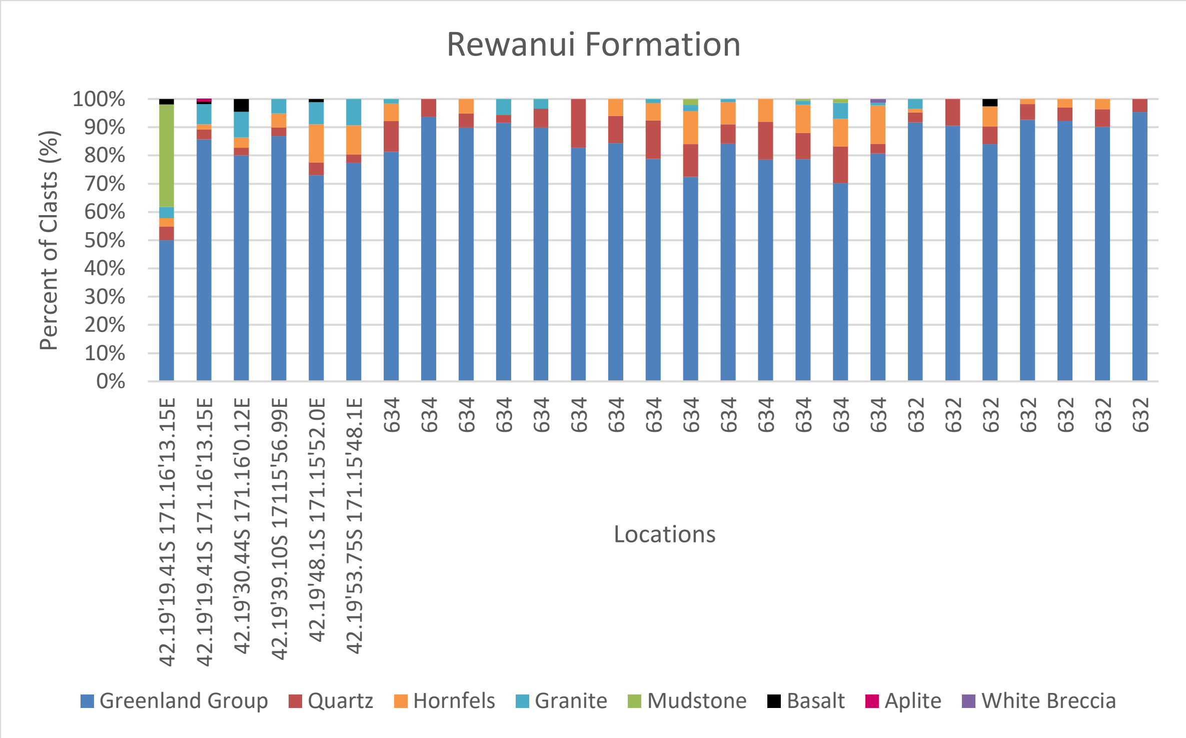

Figure 4.11 Clast counts for the Rewanui Formation.

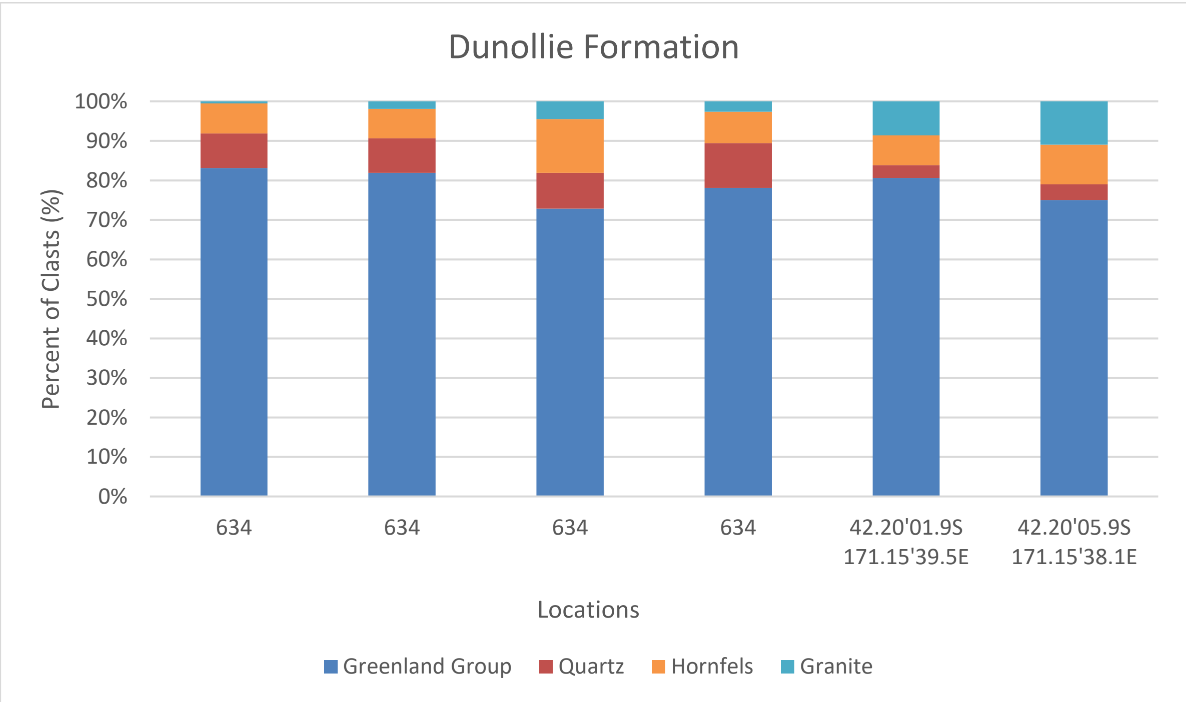

Figure 4.12 Clast counts for the Rewanui Formation.

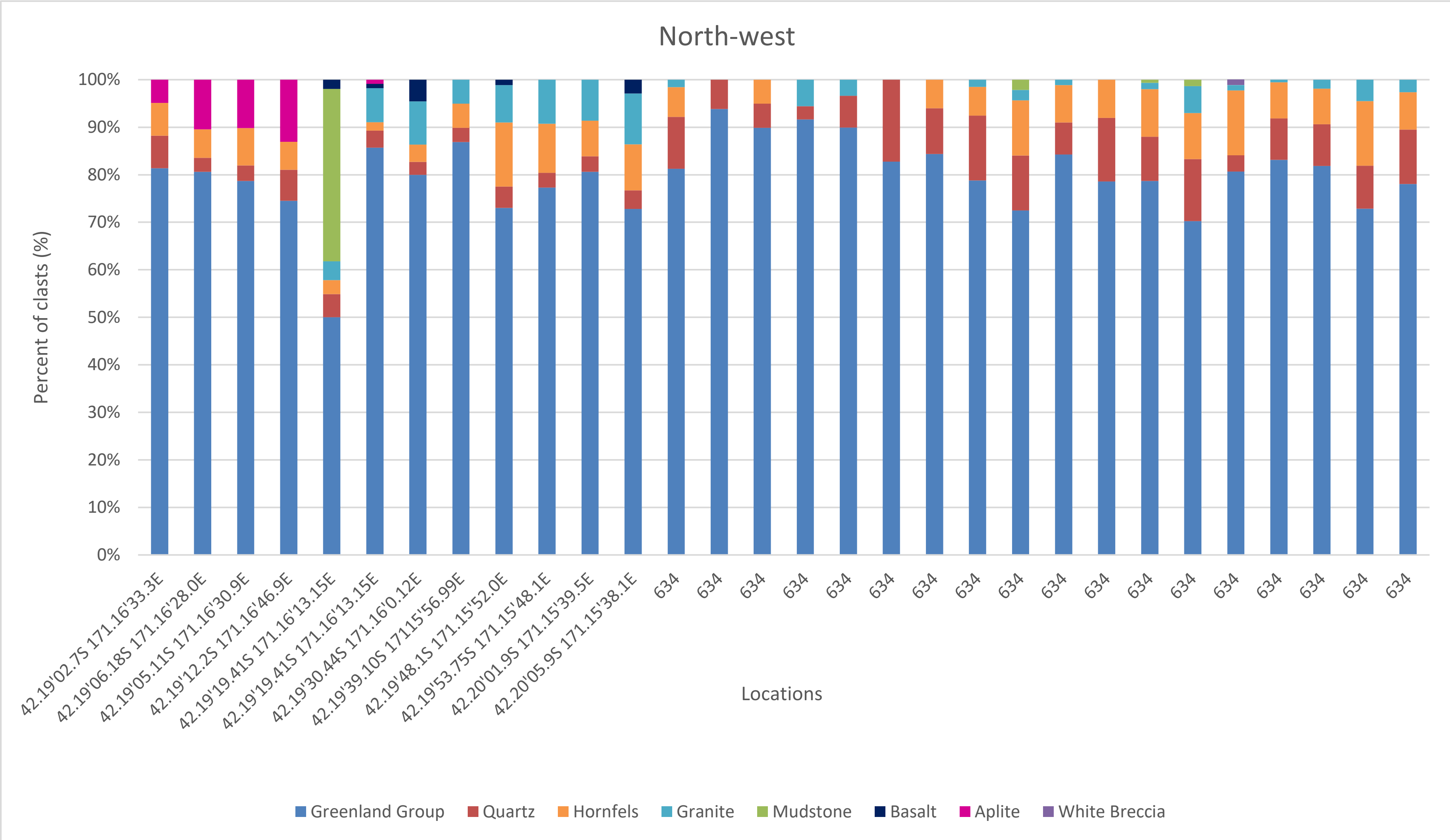

Figure 4.13 Clast counts for the north-west side of the Greymouth Basin.

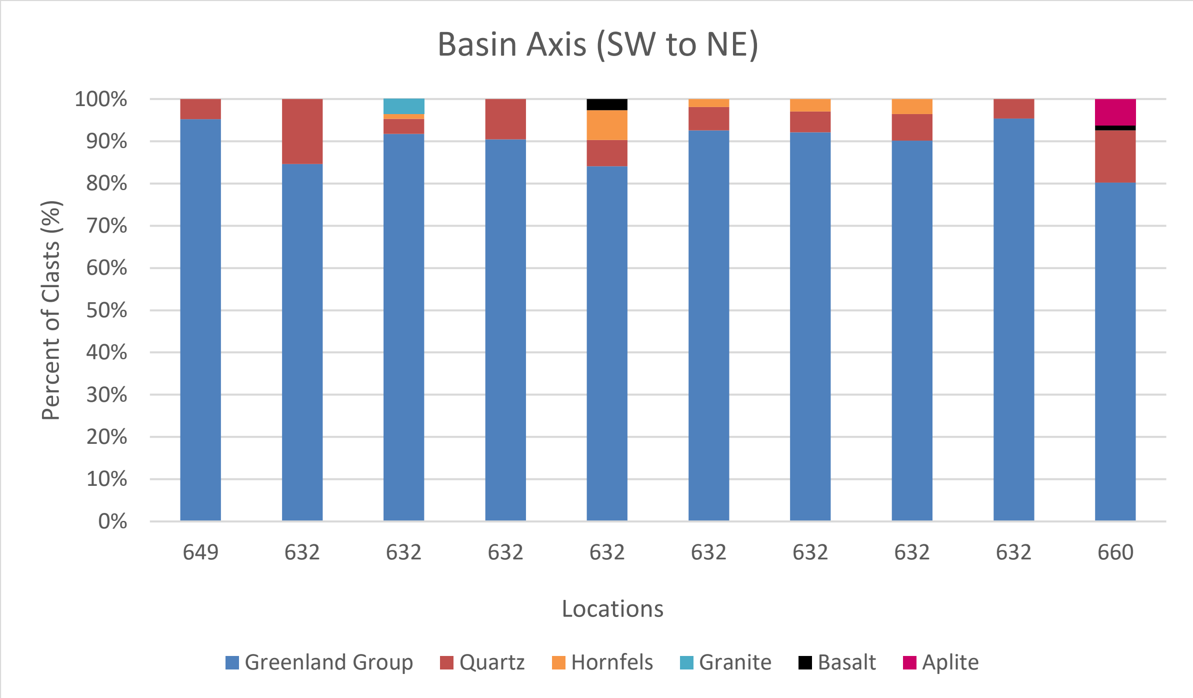

Figure 4.14 Clast counts for the Greymouth Basin axis, south-west to north-east.

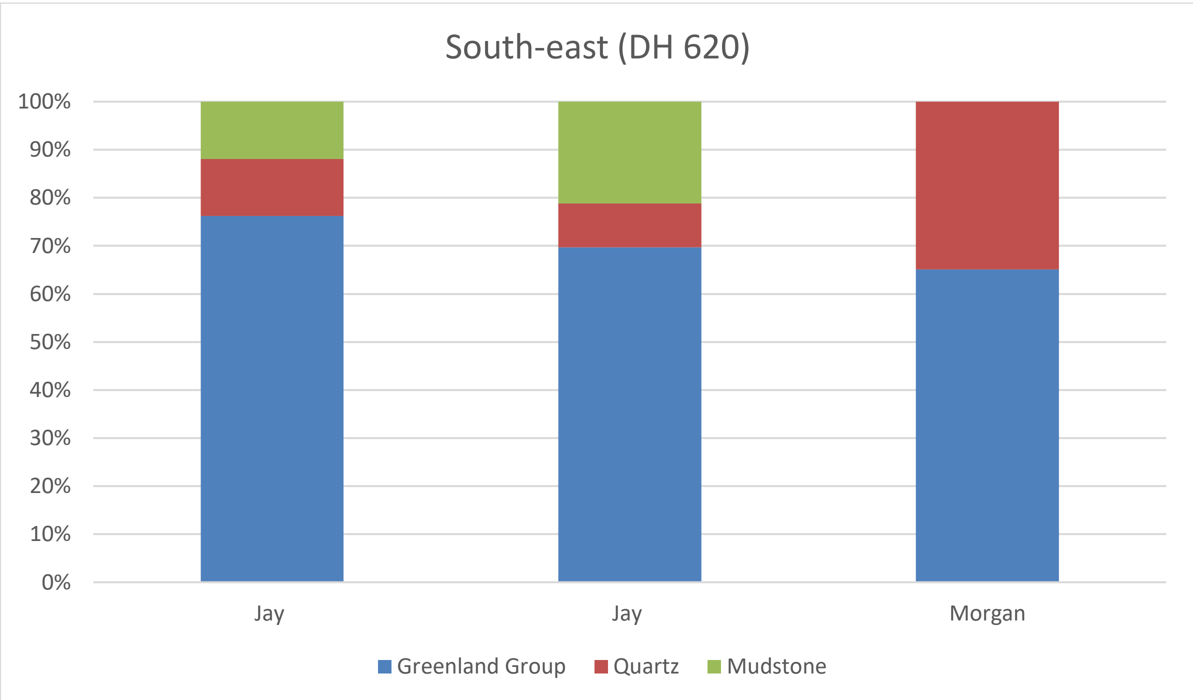

Figure 4.15 Clast counts from drill hole 620 as the south-east side of the Greymouth Basin.

Clast Count Analysis

Using the clast count results, any trends or relationships can be determined. The clast count analysis shows that the Greenland Group dominates the conglomerates from the older Jay Formation to the youngest Dunollie Formation across the basin (Figure 4.13, 4.14 & 4.15). Quartz clasts are also consistent throughout the Paparoa Coal measures as the quartz is sourced from the Greenland Group. The occurrence of aplite clasts in the lower most conglomerates (Jay and Morgan Formation), increase in appearance up section, fading out in the base of the Rewanui Formation along with the introduction of the granitic clasts. The clast counts also indicate the appearance of hornfels clasts at the same time as the aplite. The hornfels do not disappear like the aplite, but are consistently observed throughout the Paparoa Coal Measures. The granitic clasts appear in the Rewanui Formation and continue up into the Dunollie Formation. The basaltic clasts are generally only found in the Rewanui and Dunollie Formation at 12 Mile Beach outcrop, with the odd clast found in the Jay Formation in the east near the Morgan Volcanics.

The clast counts show that all of the formations coarse clastic sediments are constant up section with the exception of the Morgan Formation, with the increase in aplite and termination into the base of the Rewanui Formation.

The clast counts show that there was little difference in the composition of the conglomerates from the north-west than in the centre and south-east, other than the granitic clasts (Figure 4.13, 4.14 & 4.15). The granitic clasts are only located in the north-western side of the basin with minor influence in the centre (DH 632), and being non-existent in the south-east (Figure 4.15). This however, is due to the absence of any Rewanui Formations, coarse clastic material on the eastern side. Basaltic and hornfels clasts seem to be geographically limited to the north-west and the axis of the basin, with the exception of the Morgan Volcanics in the north-east (Figure 2.1). Otherwise the conglomerates compositionally were the same with Greenland group, quartz and some mudstone. The eastern conglomerates in the lower, older, Jay and Morgan Formations were generally consistent with the western equivalents except for the amount of aplite.

4.1.2 Granite and Basaltic Clast Geochemical Analysis

The Granitic clasts were analysed to determine the geochemistry of the clasts to compare to the possible granitic sources in the area. There are a few possible granitic plutons within the Greymouth Basin area that could be the source of these sediments. The largest of these possible source rocks is the 370 ± 5 Ma Karamea Suite (Muir et al. 1994; Tulloch 1983; Sagar & Palin 2013). The Karamea Batholith extends south from Kahu-rangi Point for nearly 200 kms to the Alpine Fault east of Greymouth, and has an average width of 20 kms (Muir et al 1996). It intrudes the Ordovician metasedimentary rock of the Greenland Group to the west and the Golden Bay Group to the east (Cooper, 1989). Large, sloped blocks of country rock are common near the steeply dipping margins of the batholith, and biotite, andalusite, sillimanite and cordierite, which were observed in the contact aureole, which is generally < I km wide (Roder & Suggate, 1990). The closest outcrop of the Karamea Suite is the Barrytown Granite to the north of the Greymouth Basin.

The younger granitic intrusions like the Rahu Suite occurred between 120 -110 Ma (Muir et al., 1994). These granitic bodies show a younging relation towards the west, from the Pearse Granodiorite in the east, which forms part of the Separation Point Batholith (119 Ma ± 2.3 Ma.), to the Buckland Granite in the west (109 ± 4 Ma.) (Muir et al., 1994). These younger granitic bodies have a higher concentration of sodium Na than the Karamea Suite (Tulloch, 1983; Muir et al., 1994; Graham & White, 1990 Tulloch, Ramezani, Kimbrough, Faure, & Allibone, 2009). The Rahu Suites Buckland granite is also a possible source for the granitic source for the Paparoa Coal Measures.

There are other granitic bodies found offshore along the West Coast with wells intercepting granitic basement (Tulloch, Kimbrough, & Waight, 1992; Andrew Tulloch, pers. comm. 2017). The Kongahu-1 is the closest well to the Greymouth Basin to intercept granitic basement. The granite was suspected to be Cretaceous in age and was deformed (Wiltshire, 1984).

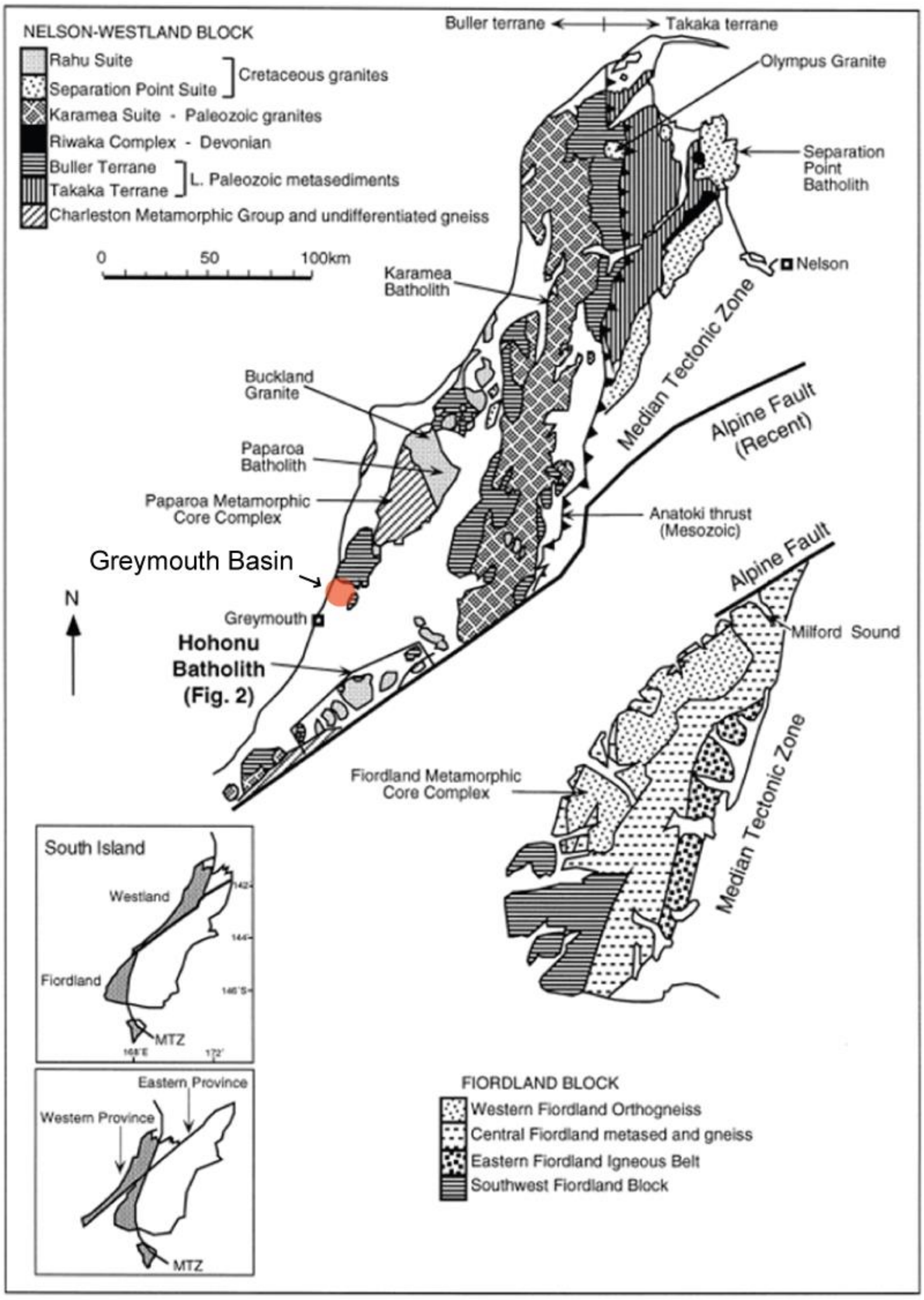

Figure 4.16 Regional geology of the Western Province of New Zealand, Edited (Waight et al., 1998).

Petrographic analysis of the granitic samples (sample 9, 12, 14, 15, 20, 21, 23, 12MB02, 12MB05 and 12MB06) revealed significant weathering of the feldspars (Table 4.1). The thin section analysis of the granite samples revealed only slight variances in composition and minerology (Table 4.1). The samples showed granitic, equigranular, anhedral crystals, phaneritic and weathered textures across the samples. Composition of the samples only varied slightly, comprising of straight and undulatory extinction quartz, plagioclase, alkali feldspar, muscovite, biotite, opaques and sericite clay. Quartz determined by its low first order birefringence and high relief was the predominant mineral in all the samples. Plagioclase feldspar was identified by the severity of chemical alteration textures, tabular laths, low first order birefringence and polysynthetic twinning. Alkali feldspar was identified by large tabular phenocrysts, low first order birefringence, minor weathering alteration and microcline and simple twinning. Muscovite appeared constantly throughout the samples as long tabular laths with parallel cleavage and a high birefringence. Biotite was not as common as muscovite but did appear in most samples (sample 9, 12, 14, 15, 20, 21, 23, 12MB02 and 12MB03). Biotite was determined by the brown pleochroism in plain polarised light, crystal habit, and birds eye extinction in cross polarised light. Opaques were present in minute quantities (<1%) throughout the samples as black in both plain and cross polarised light. Sericite and clay were present in all the samples as all the samples had experienced a degree of chemical alteration. Sericite was identified due to the presence of very fine high birefringent minerals forming in and around the feldspar crystals. Clay was determined due to the extremely fine nature of the mineral and the brown colour in plain polarised light and cross polarised light. The quartz, alkali feldspar and plagioclase feldspar (QAP) diagram determined that the samples were granite (Figure 4.17)

Sample %	Quartz %	Plagioclase %	Alkali Feldspar %	Muscovite %	Biotite %	Sericite and Clay %	Opaque's %
9	44	10	19	10	1	15	(<1%)
12	45	10	26	8	2	8	(<1%)
14	41	8	26	11	5	8	(<1%)
15	51	10	25	7	1	5	(<1%)
20	41	12	26	12	3	5	(<1%)
21	43	10	28	10	0	8	(<1%)
23	51	10	26	8	2	2	(<1%)
12MB02	42	10	25	12	2	8	(<1%)
12MB03	46	10	25	8	3	6	(<1%)

Table 4.1 Table showing the percentage of minerals and composition of granite samples.

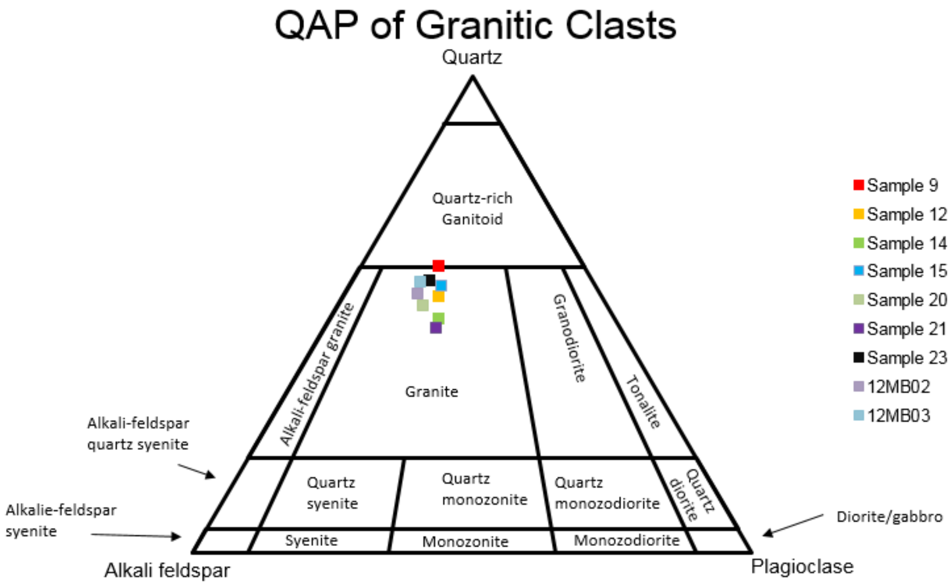

Figure 4.17 QAP of Granitic Samples

The clay content determined in the thin section analysis is due to the chemical alteration of the feldspars, predominantly the plagioclase. Therefore, to try to extrapolate the composition of the granite samples before alteration, the clay content percentages were added to the plagioclase percent’s. This will provide a more accurate representation of the plagioclase component of the granitic clast composition before weathering.

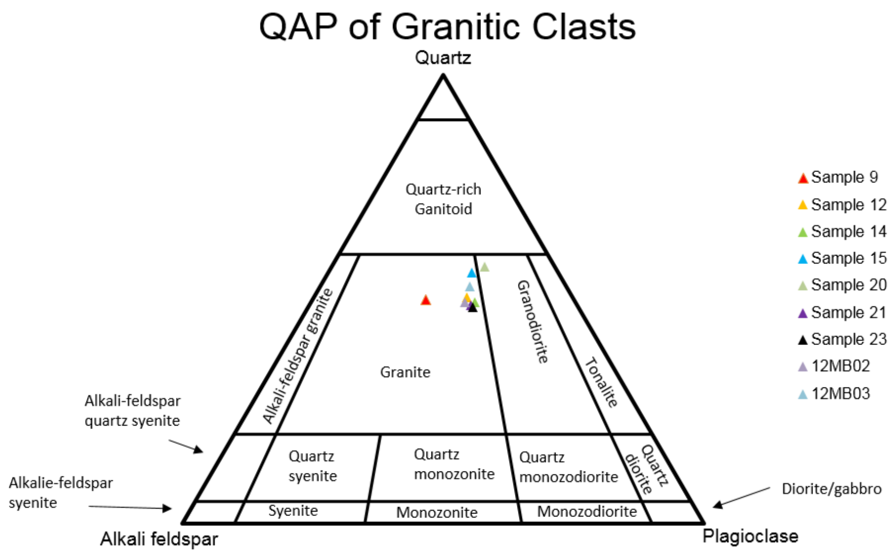

Figure 4.18 Extrapolated plagioclase QAP diagram

The results for the extrapolated data show that the granitic clasts are now slightly closer to the granodiorite area of the QAP (Figure 4.18) compared to the original data set. The larger Karamea Batholith is composed primarily of biotite and/or muscovite granites and granodiorites (Grindley 1961; Tulloch 1983; Muir et al 1996). However, confidence in the extrapolated plagioclase data cannot be placed, as it is by nature, only estimation. The extrapolation is there to try and provide an unaltered interpretation of the granites.

The Buckland granite (Rahu Suite) and Barrytown granite (Karamea Suite) are similar in terms of minerology with both suites comprising of biotite muscovite granites (Tulloch, 1973; Adams & Nathan, 1978; Tulloch 1983; Graham & White 1990). The Buckland granite typically has more muscovite than the Barrytown. The thin section analysis determined that the granitic clasts had a higher percent of muscovite than biotite. This would imply that the granitic clasts are derived from the Buckland granite and not the Barrytown granite. This is a justified conclusion; however, the Barrytown granite does still contain muscovite granites and this data alone does not provide enough conclusive evidence to determine the source of the granitic clasts from this data set.

Major and Trace Element Analysis

The granitic clast samples were sent to Spectra Chem, a company that specialise in the X-ray fluorescence and X-ray diffraction analysis. However, not all the samples that were subjected to petrographic analysis were sent to Spectra Chem as there was not enough left of the clast after thin section preparation to analyse. The clasts were analysed for the major and trace element components of the clasts. These clasts were collected from both outcrop and from drill core. The Karamea and Rahu Suite have had significant geochemical analysis of major and trace elements (Tulloch, 1983; Tulloch & Brathwaite, 1986; Muir et al., 1994; Graham & White 1990; Tulloch, 2009). The granitic suites that the Barrytown and Buckland granites represent were used in the geochemical analysis to encompass any variation in chemistry. The granitic bodies major elements analysed were; SiO_2, TiO_2, Al_2O_3, Fe_2O_3, MnO, MgO, CaO, Na_2O, K_2O and P_2O_5.

Major Elements

The major element results were used to compare the concentrations of the samples to possible parent rocks. The granitic samples were plotted on a Na_2O: K_2O: CaO (wt%) ternary diagram to visualise the percent of Na, K and Ca (Figure 4.19).

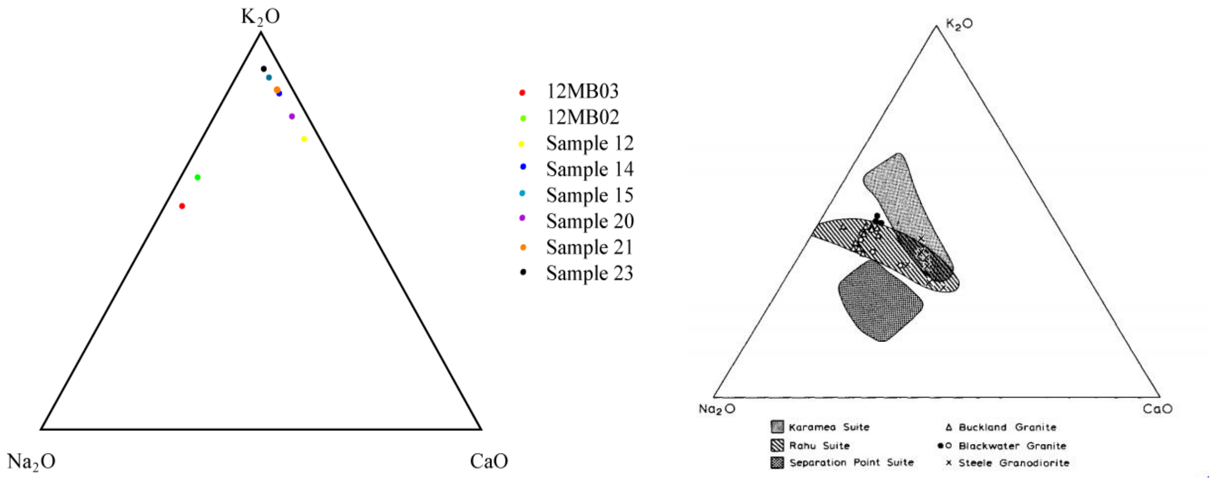

Figure 4.19 Plot of Na_2O: K_2O: CaO (wt%) comparing granite samples compared to the Karamea, Rahu and Separation Point Suites (Tulloch, 1983; Tulloch & Brathwaite, 1986; Graham & White, 1990)

Major element analysis shows that all the samples except for 12MB02 and 12MB03, had very low Na content. Plagioclase feldspar ((Na, Ca) (Si, Al)$_4$O$_8$) is comprised of both sodium and calcium in its chemical formula. The results in Figure 4.19, show that the majority of the samples are low in both sodium (Na) and calcium (Ca). These two components have been reduced due to plagioclase chemical alteration, reducing the amount of plagioclase in the samples, which subsequently reduces the amount of sodium (Na) and calcium (Ca) (Middelburg, van der Weijden, & Woittiez, 1988).

Previous geochemical analysis of major elements in the Karamea, Rahu and Separation Point Suites has been conducted by Tulloch 1983 and Tulloch & Brathwaite 1986 (Figure 4.19). The composition of the granitic suites varies slightly between the three. The Karamea Suites is relatively more potassic with a higher concentration of potassium (K) within the granite (Tulloch 1983; Tulloch & Brathwaite 1986; Muir et al. 1994; Graham & White 1990; Tulloch 2009). Rahu Suite plutons have Na/K approximately equal to 1, and plot between the Karamea and Separation Point Suite (Tulloch 1983; Tulloch & Brathwaite 1986; Muir et al 1996;

Tulloch et al 2009). The Rahu Suite is more sodium (Na) rich than the Karamea Suite, but consists of a higher concentration of potassium than Separation Point (Tulloch 1983; Tulloch & Brathwaite 1986; Muir et al 1996; Tulloch et al 2009). The Separation Point Suite has the highest Na compostion compared to the other two granitic suites (Tulloch 1983; Tulloch & Brathwaite 1986; Tulloch et al 2009). The 12MB02 and 12MB03 samples have similar concentrations of Na, K and Ca as that of the Karamea Suite samples (Tulloch 1983; Tulloch & Brathwaite 1986; Muir et al 1996; Tulloch et al 2009). The Rahu and Separation Point Suite samples are sodium rich compared to the 12MB02 and 12MB03 samples. Therefore, the major element concentrations suggest the granitic clast samples cannot be from the Rahu or Separation Point suites. However, the 12MB02 and 12MB03 samples are consistant in composition with the Karamea Suite samples, supporting the conclusion that the Karamea Suite and therefore, the Barrytown granite, is the source of these samples.

Trace element analysis was also conducted on the granitic clasts. The trace element geochemistry analysis of the clasts analysed the amounts of As, Ba, Ce, Cr, Cu, Ga, La, Nb, Ni, Pb, Rb, Sc, Sr, Th, U, V, Y, Zn and Zr in mg/kg. Chemical elements are divided into two groups, immobile and mobile, based on their geochemical distribution during weathering (Middelburg et al 1988). Elements that are immobile during weathering are Zr, Hf, Fe, Al, Th, Nb, Sc and the rare earth elements (REE) (Middelburg et al 1988). Ca, Na, P, K, Sr, Ba, Rb, Mg and Si are very mobile elements. Mobile elements are derived predominantly from leachable minerals such as feldspars and micas, whereas immobile elements are either concentrated in resistant phases or strongly adsorbed by secondary minerals (Middelburg et al 1988). The REE are mobilized or fractionated only during late stages of weathering (Middelburg et al 1988). This fractionation is caused by selective leaching of rocks, composed of both stable and unstable minerals containing REE (Middelburg et al 1988).

The trace element analysis results were used to compare the trace element profile of the samples to potential source rocks. This will determine the most likely source for the granitic clasts. The granitic clast geochemical results were plotted and normalised to chondrite, according to Sun & McDonough (1989). The results show the amount of the analysed element in mg/kg, which is the same as ppm.

The trace element analysis shows that the samples are all consistent with some variation in barium (Ba) concentrations (Figure 4.20). The sample results show a drop in barium and strontium which are both mobile elements (Middelburg et al 1988). Mobile elements are the elements most likely to be removed by weathering and chemical alteration (Middelburg et al 1988). Therefore, the drop in these elements is likely due to weathering and chemical alteration of the samples.

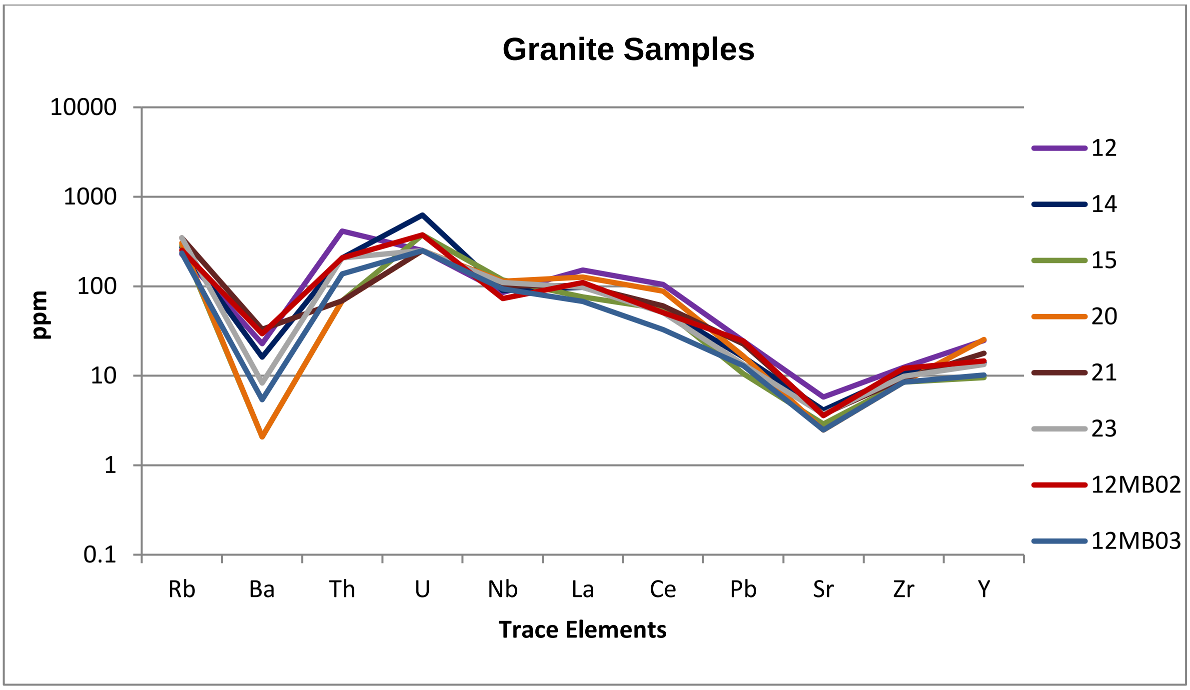

Figure 4.20 Granitic clasts trace element profile normalised to Chondrite (Sun & McDonough, 1989).

The trace element profiles of the two possible source rocks were overlaid with the granitic clast profiles. The trace element profile that is the most similar suggests the two data sets are from the same source. Therefore, the provenance of the granitic clast samples will be confirmed.

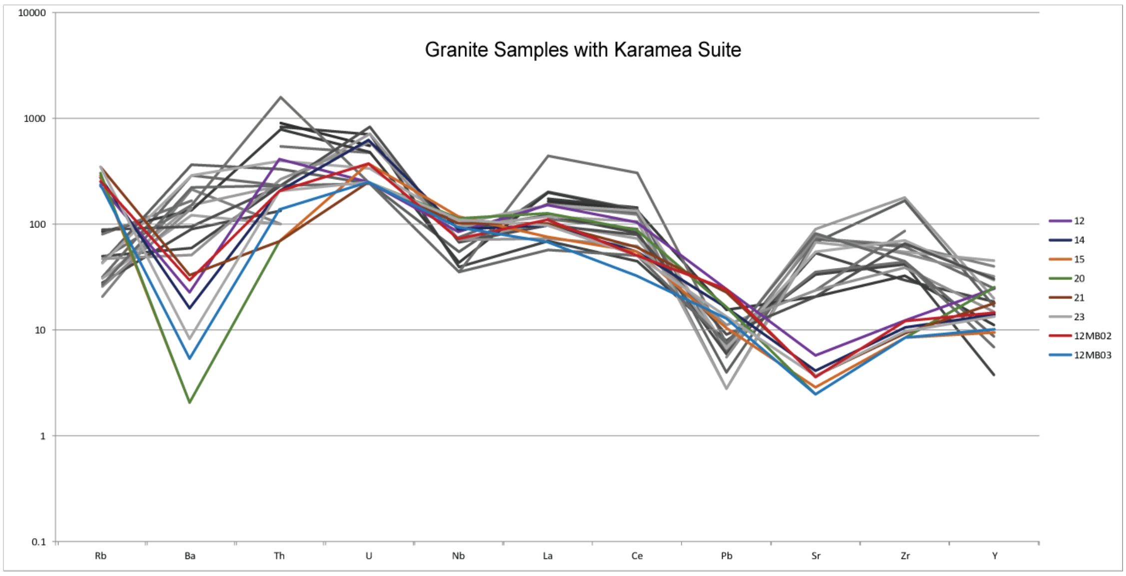

Figure 4.21 Granitic samples superimposed on Karamea Suite.

The Karamea Suites trace element profile was plotted using the Karamea Suite Petlab data set from GNS Science New Zealand (Strong et al., 2016). This data set has over 150 samples of the Karamea Suite analysed. The trace element data from this data set was used to create, the normalised to chondrite, trace element profile (Sun & McDonough 1989). The data set for the Karamea Suite has been selected to provide the best representation of the trace element profile trend. This was due to the overwhelming amount of data for particular elements.

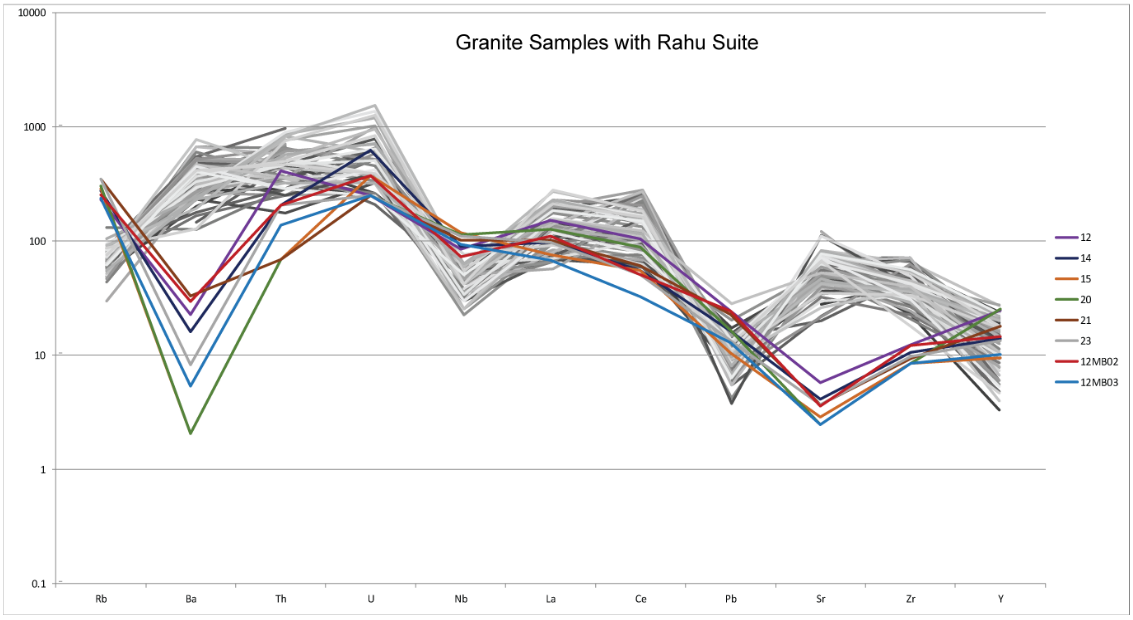

Figure 4.22 Granitic samples superimposed on Rahu Suite.

The Rahu Suites trace element profile was plotted using the Rahu Suite Petlab data set from GNS Science New Zealand (Strong et al., 2016). This data set also has over 150 samples of the Rahu Suite analysed. The trace element data from this data set was used to create, the normalised to chondrite, trace element profile (Sun & McDonough 1989). The Rahu Suites spider diagram is more consistent than the Karamea Suites profile, concluding that there is more variance in the Karamea Suites compositions. This is not surprising as the Karamea Suite is the largest in the western province (Figure 4.16) and therefore more chemical variance spatially.

Both the Rahu and Karamea Suites trace element profiles are very similar with only slight variations. The Karamea Suites trace element profile shows a higher niobium (Nb) concentration (Figure 4.21) than the Rahu Suite (Figure 4.22). However, the Rahu Suites barium (Ba) concentrations are slightly higher than Karamea Suites. The slight variations in the trace element composition of the two suites will make the comparison more difficult.

The granite sample trace element overlays illustrate the granite samples significant variation on concentration between rubidium (Rb), barium (Ba) and strontium (Sr). Neither, the Karamea or the Rahu Suites have these significant high or drops in concentration of these elements. However, this does not mean that the granitic samples could not come from either source. Barium and strontium are both mobile elements, which are easily removed during chemical alteration (Middelburg et al 1988). Mobile elements are derived mainly from leachable minerals such as feldspars and micas (Middelburg et al 1988). The weathering of the granitic samples has not only affected the major element component (Figure 4.19) but also has influenced the trace elements. Taking the drop in mobile elements associated with weathering into consideration, the trace element profiles look more like the suspected source rocks.

The significant variations in the concentrations of barium and strontium in the granitic samples are due to chemical alteration and mobile element (Middelburg et al 1988). However, the higher variation in rubidium (Rb) is interesting as rubidium (Rb) is also considered a very mobile trace element (Middelburg et al 1988). The amount of Rb should therefore decrease, along with the other more mobile elements. The higher concentration of Rb is most likely a result of the degree of weathering the granite samples have undergone (Middelburg et al 1988).

The granitic samples trace element profile (excluding the explained variance in Rb, Ba and Sr due to weathering) is quite similar to both the Karamea and Rahu Suite. The Karamea Suite is confirmed to have a high Rb content and low Sr and Ba (Tulloch et al. 2009). The granite samples composition is close enough to the two suites, that it could be justified in determining that these clast samples came from either the Karamea or Rahu Suite (Figure 4.21 & 4.22). However, the Karamea Suites trace element profile seems to be the closest match as the thorium (Th) and niobium (Nb) concentrations seem to be more aligned. Thorium and niobium are immobile elements that do not decrease in concentration due to weathering and therefore, make a good reference point to compare compositions (Middelburg et al 1988). Therefore, the Karamea Suite is the most likely source of the two granitic sources for the granite clasts.

However, there is a possibility that the clasts come from a mixed source, but that is unlikely due to the major elements results (Figure 4.19) and the petrographic analysis showing a constant grouping (Figure 4.17). Considering the petrographic analysis, major element analysis and trace element analysis all conclude one source, it is likely the parent rock of the granitic clasts in the Paparoa Coal Measures comes from one source.

After discussions with a local expert about the granitic geochemistry results, it was determined that neither the Rahu (Buckland granite) nor the Karamea (Barrytown granite) Suites were the parent rock for the granitic clasts in the Paparoa Coal Measures (Andrew Tulloch, pers. comm. 2017). The geochemistry of the Granitic samples best fits an A-type granite, which typically have low barium (Ba) and strontium (Sr) (Winter, 2010; Andrew Tulloch, pers. comm. 2017). A-type granites are typically shallowly emplaced and associated with tectonic rifting (Winter, 2010). There is evidence of A-type granites on the West Coast (Tulloch et al., 1992), but this granite would have to be located offshore.

Aplite Clasts

Aplite clasts were found predominantly in the Morgan Formation on the western side of the basin with a few occurrences in the bottom of the Rewanui Formation. The occurrence in only the older sediments and the bottom of the Rewanui support the theory of a granitic pluton unroofing. This is also supported with the occurrence of the granitic clasts after the disappearance of the aplite.

Geochemical analysis was conducted on these clasts by Spectra Chem to determine the major and trace elements of the clasts. Geochemical analysis was conducted on two aplite samples. Major elements analysed were; SiO_2, TiO_2, Al_2O_3, Fe_2O_3, MnO, MgO, CaO, Na_2O, K_2O and P_2O_5.

Major Elements

The major element results were used to compare the concentrations of the samples to possible parent rocks. The aplite samples were plotted on a Na_2O: K_2O: CaO (wt%) ternary diagram to visualise the percent of Na, K and Ca (Figure 4.23).

The major element analysis of the aplite samples reveals a very low concentration of sodium (Na) and an almost non-existent concentration of calcium (Ca). Subsequently, the concentration of potassium (K) is extremely high.

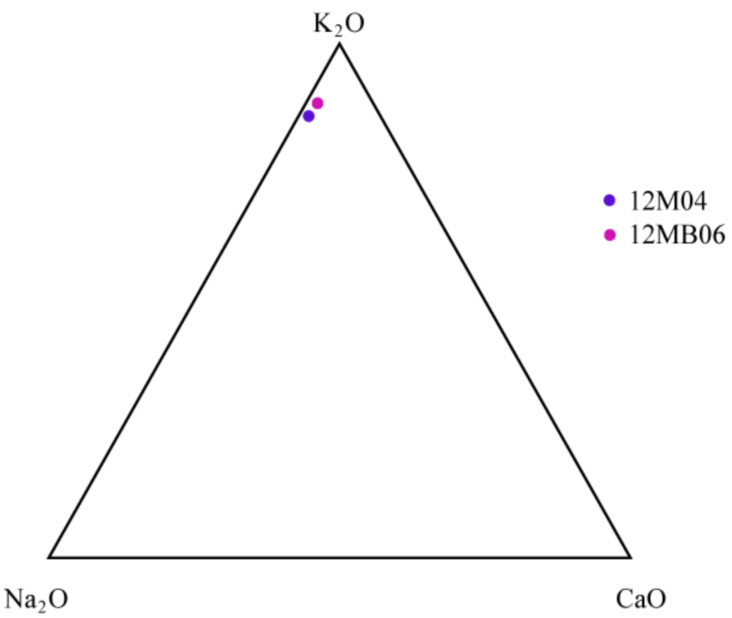

Figure 4.23 Plot of Na_2O: K_2O: CaO (wt%) for aplite major elements.

Aplite is essential a pegmatite and pegmatites form in the last stages of the pluton cooling (Winter, 2010). Therefore, the high concentration of potassium is consistent with the formation of a pegmatite as it is concentrated in element that forms last in Bowen's reaction series (Winter, 2010). This confirms the origin of the clast and supports the theory of an unroofing pluton in the west of the Greymouth Basin.

Trace Element Analysis

The trace elements analysed were of As, Ba, Ce, Cr, Cu, Ga, La, Nb, Ni, Pb, Rb, Sc, Sr, Th, U, V, Y, Zn and Zr. The aplite clasts trace element analysis results were normalised to chondrite according to Sun & McDonough (1989). The trace element profile of the aplite is shown in figure 4.24.

The trace analysis of the aplite clasts is reasonably consistent with each other (Figure 4.24). The drop in barium (Ba), lead (Pb) and strontium (Sr) is likely due to weathering as these are mobile elements (Middelburg et al 1988). What is interesting is the high concentration of uranium at almost a 1000 ppm. Granite plutons can contain high concentrations of uranium (U) which due to the incompatibility of the element, concentrates during the final cooling of the pluton (Winter, 2010). This high concentration supports the conclusion that this is aplite, as it forms in the final stages of cooling as a pegmatite.

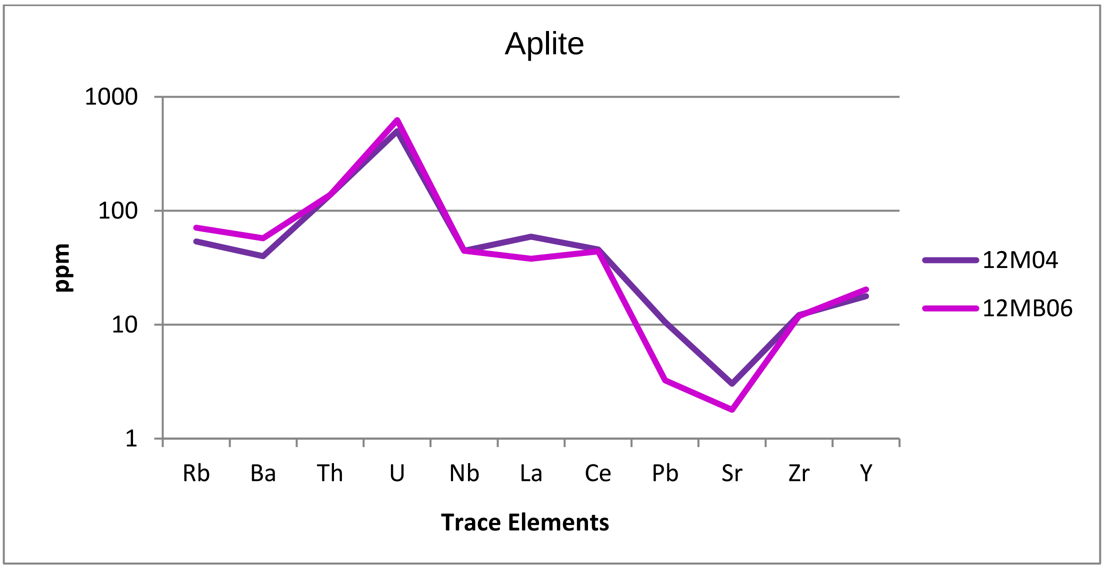

Figure 4.24 Trace element analysis of aplite clasts, normalised to chondrite according to Sun & McDonough (1989).

Suspected Basalt Clasts

There were multiple very hard, dark clasts found in the Rewanui Formation, which were thought to be small basaltic clasts. Petrographic and geochemical analysis results concluded that not all the suspected basalt clasts were in fact basalts. Petrographic analysis of these clasts showed that in fact some of these clasts were hornfels.

Geochemical analysis was conducted on these clasts by Spectra Chem to determine the major and trace elements of the clasts. Geochemical analysis was conducted on nine of suspected basaltic clasts. Major element analysis of these clasts resulted in five of the 11 suspected clasts possibly being basaltic clasts. The silica composition of the other six clasts was far too high to be considered basalts. Major elements analysed were; SiO_2, TiO_2, Al_2O_3, Fe_2O_3, MnO, MgO, CaO, Na_2O, K_2O and P_2O_5.

The five suspected basalt clasts were plotted on a total alkali and silica (TAS) diagram (Le Bas, Maitre, Streckeisen, Zanettin, & IUGS 1986). The figure shows that all but sample 12MC04, fall around the basaltic andesite area of the graph (Figure 4.25). Sample 12MC04 falls in the andesite section of the TAS diagram and is most likely a hornfels clast (Figure 4.25).

The major element analysis of the suspected basalt clasts shows that these clasts are basaltic with two samples (Sample # 8 and 12MC04) being classified as andesite (Figure 4.25). All five of the samples were clasts taken from the Rewanui Formation at the 12 Mile Beach outcrop.

These results provide evidence that there was some form of volcanism on the western side of the basin. This indicates that there were two sources of volcanism, each at opposite sides of the basin, one east (Morgan Volcanics) and one west (Rewanui basalt clasts). However, the occurrence of these volcanic clasts in the Rewanui Formation on the western side of the basin, suggests that the volcanism on the western side occurred longer than on the eastern side of the basin.

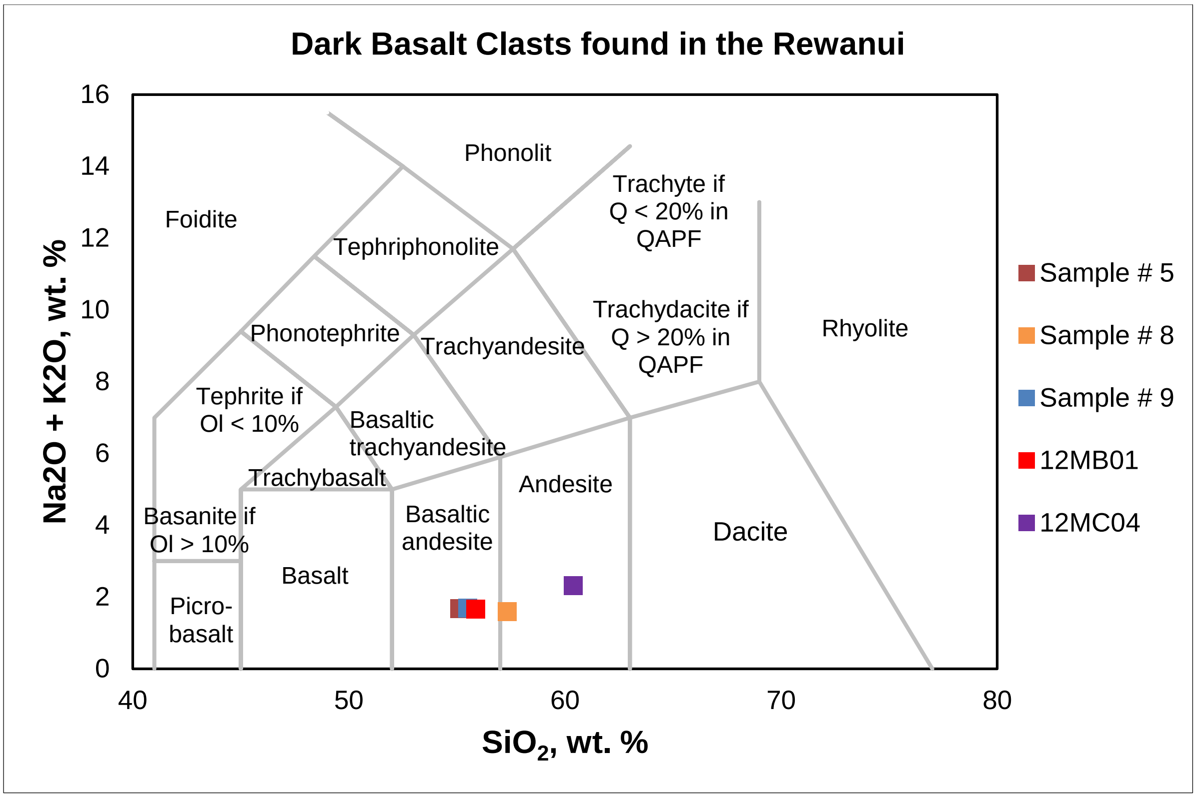

Figure 4.25 TAS diagram showing the suspected basalt clasts (Le Bas et al 1986).

Trace Element Analysis

The trace elements analysed were of As, Ba, Ce, Cr, Cu, Ga, La, Nb, Ni, Pb, Rb, Sc, Sr, Th, U, V, Y, Zn and Zr. The suspected basalt clasts trace element analysis results were normalised to chondrite according to Sun & McDonough 1989. The trace element profile of the suspected basalts is shown in figure (Figure 4.26).

The trace element analysis of the suspected basalt clasts found in the Rewanui and Dunollie Formations show high concentrations of all the trace elements (Ba,Th, U, Nb, La, and Ce) with the exception of rubidium (Rb), lead (pb) strontium (Sr), zirconium (Zr) and yttrium (Y) comparatively. These concentrations are typically high for basalt but not outside the ranges (Roex, Späth, & Zartman, 2001).

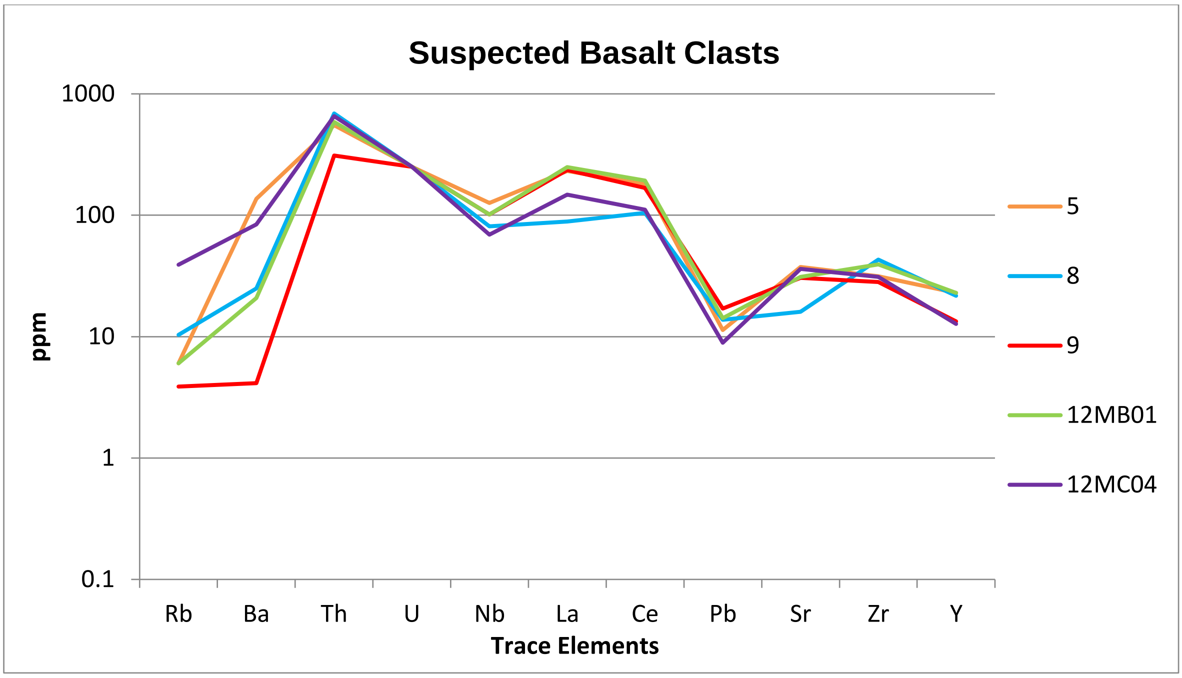

Figure 4.26 Suspected Basalt Clasts.

The suspected basaltic clasts have compelling evidenced to be determined as basaltic clasts. This has implications for the provenance of the coarse clastic sediments on the western side of the basin. The presence of these basaltic clasts indicates that there had to be a volcanic source on the western side of the Greymouth basin. There have been previous suggestions of a possible source on the West Coast (Newman, 1985)

4.1.3 Weathering

Weathering was a considerable issue when dealing with all stages of sample analysis. Weathered hand samples became more ambiguous and harder to identify as the appearance of the clasts was altered. This made some clasts hard to categorise during clast counts and descriptions. The clasts samples from the core were generally smaller than at the 12 Mile Beach outcrop. This inferred that they had been transported further and were more susceptible to weathering due to size.

Petrographic analysis was made more difficult as the chemical alteration of minerals primarily the feldspars, made determining the overall compositions of the samples difficult. Chemical alteration changes the appearance of the mineral, making some mineral characteristics altered and harder to identify.

Weathered clasts primarily caused issues with the geochemical analysis. Some of the clasts had considerably high loss on ignitions (LOI's) during sample preparation for XRF analysis. As the samples are melted to 1000°C during the preparation any organic material or water is lost. Therefore, the high LOI's indicate a large portion of the rock is gone due to the melting. The water content indicates the clay content, as clays contain water and the clay content indicates weathering. Subsequently, the degree of LOI can indicate the degree of weathering.

The granitic clasts, in particular the clasts from the core, had high LOI's which infers high degree of weathering. This was confirmed with petrographic analysis and the geochemical analysis.

The major element analysis was affected by the degree of weathering. Weathering removes the more mobile elements as they get removed from the rock by solution (Winter, 2010). Therefore, the less stable and more mobile elements according to Bowen's reaction series, weather away into solution first down the series till ending at quartz (Winter, 2010). Leaving the less mobile elements concentrated relative to the whole rock as the less stable more mobile elements are removed.

Trace elements are also susceptible to weathering with some being more mobile than others depending on the degree of weathering (Middelburg et al., 1988; Winter, 2010). Rubidium (Rb), barium (Ba), lead (Pb) and strontium (Sr) are the identified trace elements that were affected by weathering throughout the samples and these are all considered mobile (Middelburg et al., 1988; Winter, 2010). Therefore, low concentrations of these elements in weathered samples need to be considered with scepticism as they are likely skewed from weathering.

Weathering is prevalent throughout all of the samples collected to some degree and needs to be considered during interpretation of the data.

4.2 Sandstone Provenance

Sandstone dominated the eastern side of the basin with most of the sandstone samples coming from that side. There were however, plenty of sandstone beds intercepted by the drill core and along 12 Mile Beach. Before and during the point counting, the types of grains and minerals encountered had to be distinguished. Throughout the point counting process a total of 17 distinctions and categories were created for the grains and minerals that were counted.

The 17 categories were; undulatory quartz, polycrystalline quartz, strained polycrystalline, polysynthetic plagioclase, microcline alkali feldspar, stained alkali feldspar, weathered feldspar, muscovite, biotite, siltstone, mudstone, schist, basaltic, unknown lithic, opaques, matrix and organic fragments.

Undulatory quartz was found in every sample point counted and was also the most predominant constituent in most of the samples (Figure 4.27). Undulatory quartz is formed due to stress that is applied to the quartz grain (Figure 4.27). The quartz crystals atomic lattice is plastically or ductilely deformed as quartz crystals have several potential slip systems with different orientations. It is these characteristics that enhance the quartz crystals with the ability to accommodate stress (Winter 2010). Therefore, as the crystal is rotated around the stage, due to the deformation in the crystals lattice, the extinction moves through the crystal like a wave of shadow. The grains were sub-angular to angular, fractured and sutured grains. Undulatory quartz is a main component of all the sandstones counted across the basin with varying percentages ranging from 16% to 90.5%.

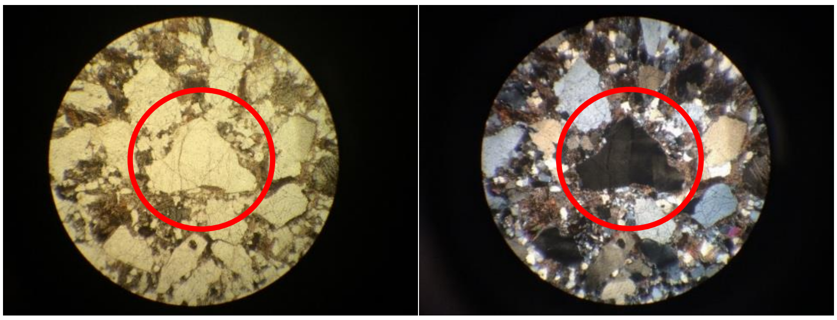

Figure 4.27 Undulatory quartz in plain polarised and cross polarised light (circled), sample 36 from drill hole 660 in the Rewanui Formation at a depth of 102.6m.

Polycrystalline quartz is a grain that is comprised of multiple individual quartz crystals and can be found in both igneous and metamorphic terranes, but very rare in igneous and always indicates a degree of strain (Basu et al., 1975; Basu, 1985; Cullers et al., 1988). Polycrystalline quartz showing two distinct crystal sizes within a grain is indicative of a strong metamorphic origin, as well as a high ratio of polycrystalline quartz to total quartz, which also suggests a metamorphic origin (Pettijohn et al., 1972; Basu et al., 1975; Basu, 1985; Cullers et al., 1988). The polycrystalline quartz had irregular boundaries between the quartz grains with the overall grain sub-rounded to angular with varying degrees of fracturing, from none to major (Figure 4.28). Polycrystalline quartz was variable across the basin and samples with percentages ranging from 0% to 36.8%.

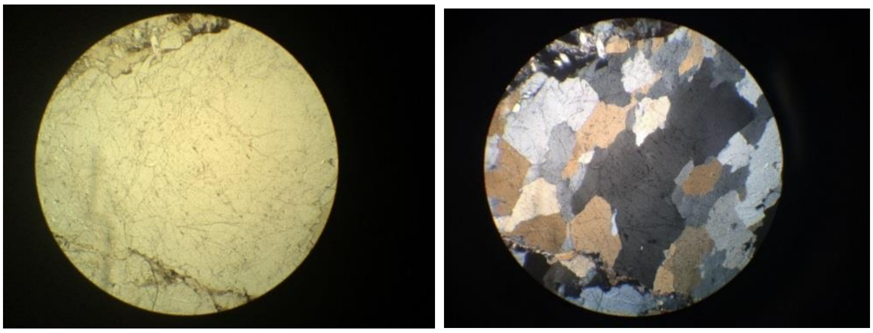

Figure 4.28 Polycrystalline quartz in plain polarised and cross polarised light, sample 42 from drill hole 660 in the Rewanui Formation at a depth of 1018.2m.

Strained Polycrystalline quartz grains are polycrystalline grains that are comprised of more elongate and strained quartz constituents (Pettijohn et al., 1972; Basu et al., 1975; Basu, 1985; Cullers et al., 1988). These polycrystalline quartz grains have been deformed, due to plastic or ductile stress as the subdomains have tried to accommodate the forces. The boundaries between the quartz grains are irregular, sub rounded to angular grains, with the quartz crystals themselves elongate, irregular and angular (Figure 4.29). Strained polycrystalline grains were not as common as the normal polycrystalline grains, but were present in a good portion of the samples ranging from 0% to 4.2% percent across all of the samples.

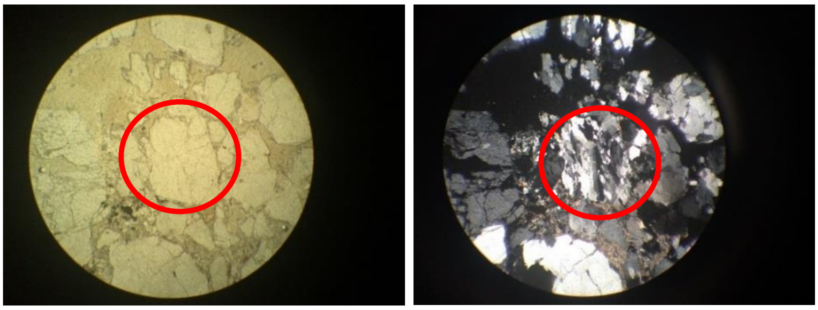

Figure 4.29 Strained polycrystalline quartz in plain polarised and cross polarised light (circled), sample 50 from drill hole 660 in the Rewanui Formation at a depth of 149.9m.

Polysynthetic twinned plagioclase also known as multiple twinning, appears like a barcode on the plagioclase feldspars in cross polarised light. The twinning appears as part of the crystal lattice, is oriented a different way which gives that part of the crystal a different extinction angle (Winter, 2010). This gives the crystal a striped appearance as it is rotated around the microscope stage (Figure 4.30). Polysynthetic twinned plagioclase was stained pink by the stain. Some grains that did not show clear twinning were also stained pink and thus were counted as plagioclase feldspar (Figure 4.30). The grains were broken or fractured and sub-angular to angular. Most had minor weathering features with some sericite filled holes. This category and the occurrence of the polysynthetic and stained plagioclase, was not a major component in the point counts as percentages ranged from 0% to 5%.

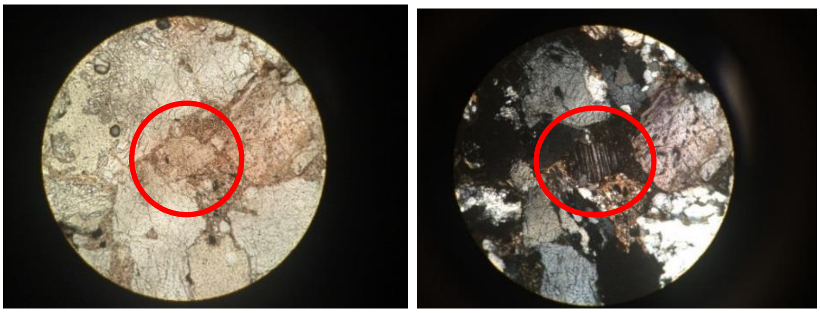

Figure 4.30 Polysynthetic feldspar in plain polarised and cross polarised light (circled), sample 49 from drill hole 660 in the Rewanui Formation at a depth of 137.2m.

The alkali feldspar microcline was quite common throughout the samples and, like the polysynthetic twinning, microcline twinning is both unique and obvious (Winter 2010). It is also the most stable of the feldspars at low temperature, and pressure making it more resistant to weathering than other feldspars (Pettijohn et al., 1972;

Basu, 1985; Cullers et al., 1988; Winter, 2010). Microcline twinning appears cross hatched in thin section under cross polarised light with twins crossing perpendicular to each other (Figure 4.31). Microcline is common in igneous, metamorphic and sedimentary rocks. These grains were sub-angular, some tabular with irregular broken ends, and some were fractured and slightly weathered. The occurrence of this mineral ranged from 0% to 10.7%, over all of the sandstone point counts

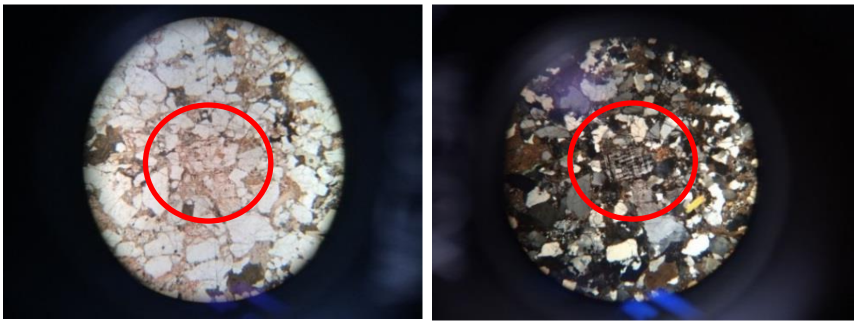

Figure 4.31 Microcline alkali feldspar in plain polarised and cross polarised light (circled), sample 42 from drill hole 660 in the Rewanui Formation at a depth of 118.2m.

Stained alkali feldspar was put in a category of its own as the yellow stain applied to the alkali feldspars stuck to the crystal grains and was more constant than the plagioclase stain throughout the thin sections. This was confirmed with the muscovite laths being stained as well, due to the potassium in their composition. These crystals were not twinned as any stained and twined alkali feldspar was put into the twinned microcline category. The crystals were often sub-angular to angular, weathered, fractured, yellowy orange in plain polarised light due to the stain and low first order birefringence in cross polarised light (Figure 4.32). This category was not common with a range of 0% to 7.6%, over all of the point counts.

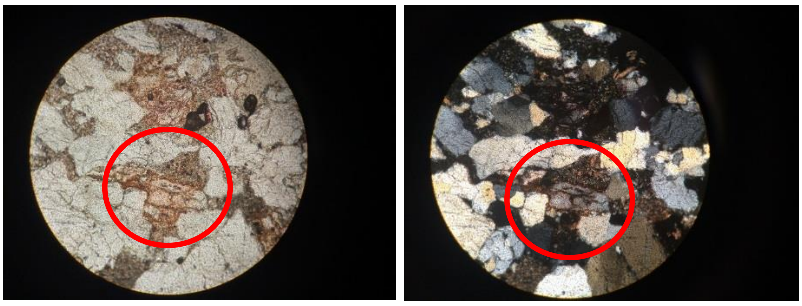

Figure 4.32 Stained feldspar in plain polarised and cross polarised light (circled), sample 49 from drill hole 632 in the Rewanui Formation at a depth of 415.8m.

The weathered feldspar category was used for feldspar grains that were not twinned or stained, but exhibited a range of weathering. The range extended from minor weathering in or around a feldspar crystal to the indistinguishable feldspar remnants of an individual crystal. The extreme end of this range had almost completely altered to clay or sericite and looked a lot like a fine grained sand matrix (Figure 4.33). However, this very fine grained matrix usually had a defined crystal habit which matrix should not have. This category likely included the majority of the plagioclase feldspar component, as plagioclase is more susceptible to weathering than alkali feldspar with a range of 0% to 50.3% percent across all of the point counts.

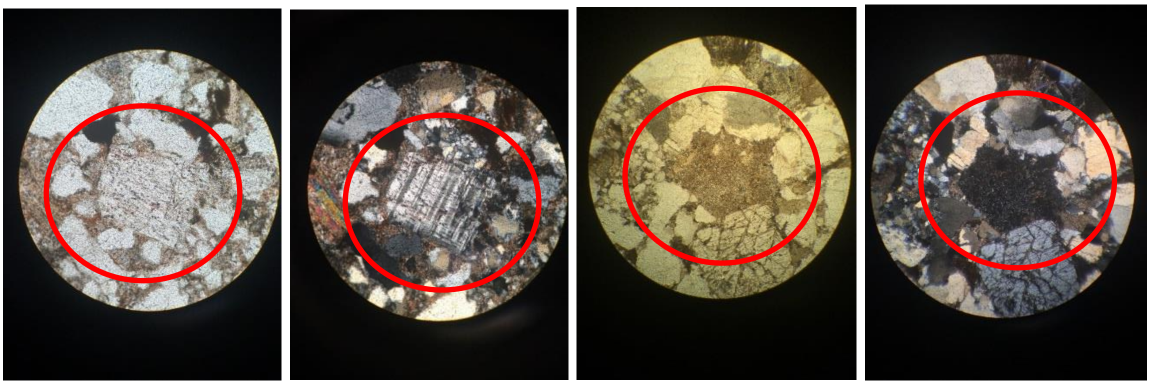

Figure 4.33 Weathered feldspars in plain polarised and cross polarised light (circled), sample 78 from drill hole 632 in the Rewanui Formation at a depth of498.1m.

Muscovite was observed in many of the thin sections and point counts. It was observed as clear in plain polarised light as small fragmented, large thin tab and was often bent by other grains due to compaction of the sediment (Figure 4.34). These tabular grains also had a high colourful birefringence in cross polarised light. The muscovite was also often stained yellow as the potassium in them has reacted with the yellow stain. Muscovite was present with a range of 0% to 9.4% percent across all of the point counts.

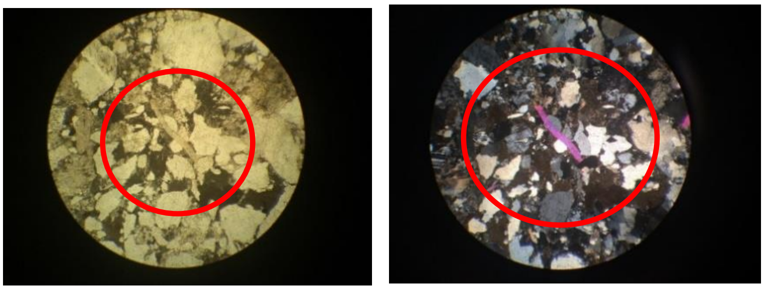

Figure 4.34 Muscovite in plain polarised and cross polarised light (circled), sample 58 from drill hole 660 in the Rewanui Formation at a depth of 161.5m.

Biotite was not as abundant as muscovite but was observed in most point counts. Biotite was observed as small to large tabs, often bent, like the muscovite tabs, but was predominantly on the smaller side on the size range. It was identified by the brown, pleochroic colour in plain polarised light and birds eye extinction in crossed polarised light (Figure 4.35). Biotite occurred from 0% to 4.7% in sample point counts.

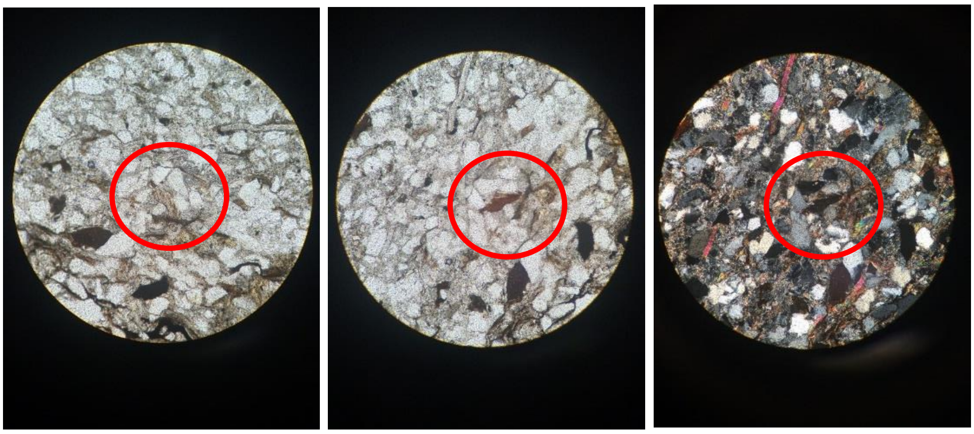

Figure 4.35 Biotite in plain polarised and cross polarised light (circled), sample 12 from drill hole 634 in the Rewanui Formation at a depth of 484.25m.

Siltstone grains were sporadically spotted throughout some of the samples, as well rounded, very fine to fine grained grains in the sandstones. These were identified as Greenland Group lithics due to their fine grained, rounded, quartz rich, slight fabric/foliated appearance (Figure 4.36). Greenland Group lithics were distinguished from weathered feldspars by grain shape and grain textures (Figure 4.36). These small grains of Greenland Group were very similar in appearance and composition to their larger counterparts found in the conglomerate clast counts. Greenland Group counted grains were not very common with a range of 0% to 4.6% across all of the samples.

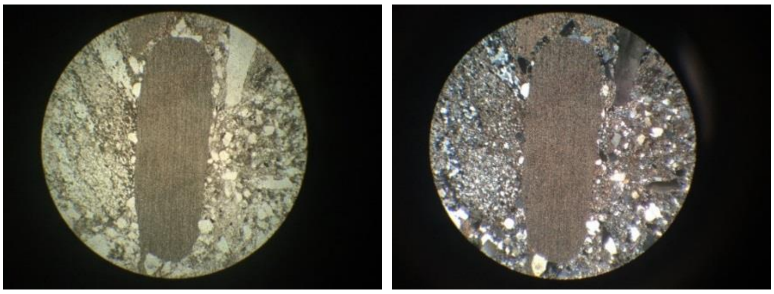

Figure 4.36 Greenland Group lithic in plain polarised and cross polarised light (circled), sample 80 from drill hole 632 in the Rewanui Formation at a depth of 461.7m.

Mudstone grains were countered in a number of point counts, often irregularly shaped and squished by other grains. These appeared as brown in plain polarised light, dark brown in cross polarised light, sometimes bedding or foliations were visible (Figure 4.37). Comprised of clay and fine silt particles the composition of the mudstones was indistinguishable other than mud. The mudstone grains were not common, a range of 0% to 6.4% in most samples. The one exception was sample 94 from the Rewanui Formation in drill hole 632, with 26% mudstone grains.

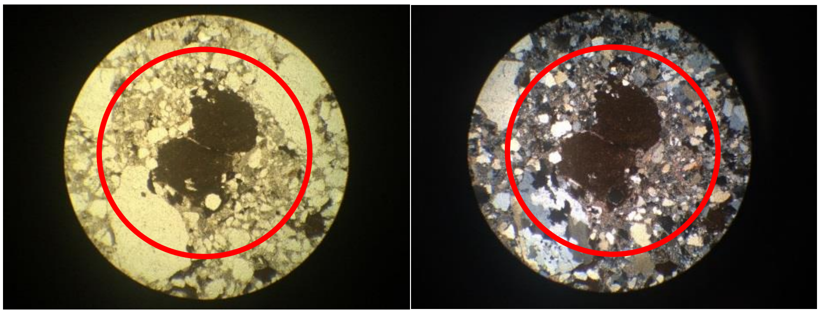

Figure 4.37 Mudstone lithic in plain polarised and cross polarised light (circled), sample 94 from drill hole 632 in the Rewanui Formation at a depth of 291m.

Schist rock fragments were not common but were encountered in a number of point counts. These grains were identified by the large accumulation of muscovite aligned, all parallel together (Figure 4.38). Schists form compositional bands and often have layers of micas, biotite and muscovite. The accumulations of muscovite were identified by the same characteristics used to identify the smaller muscovite tabs; colourless in plain polarised light and a high colourful birefringence in cross polarised light with birds eye extinction. The percentages of occurrence of schist grains were very low with percentages ranging from 0% to 1%.

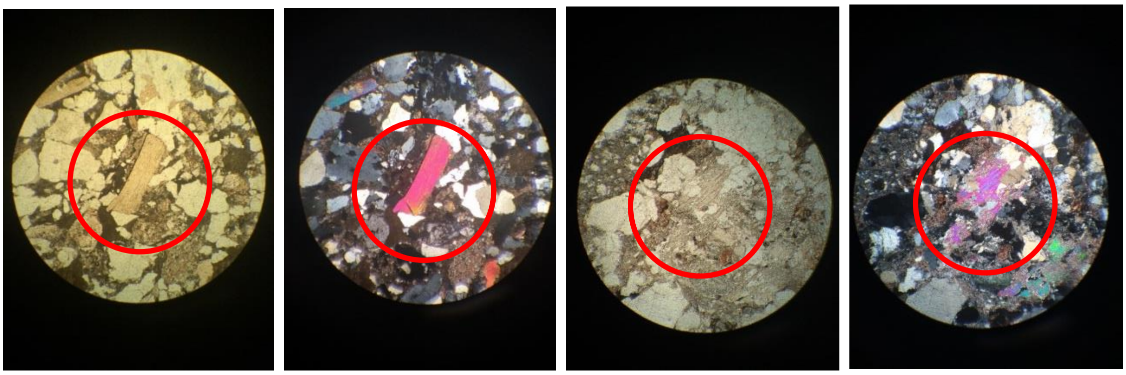

Figure 4.38 Schist lithics in plain polarised and cross polarised light (circled), sample 34 from drill hole 660 in the Rewanui Formation at a depth of 137.2m.

Basaltic grains were rare but easily recognised, as the grains had interlocking crystals at different orientations and often had sharp spindle like crystals. The grains were very fine grained, sub-rounded, dark very fine grained groundmass with the odd vesicle. The spindly lath like minerals cross cutting through the groundmass are likely to be feldspars, but identification was difficult as there was no twinning, and the crystals were small (figure 4.39). Volcanic grains were counted in six different samples ranging from 0% to 1% over all samples.

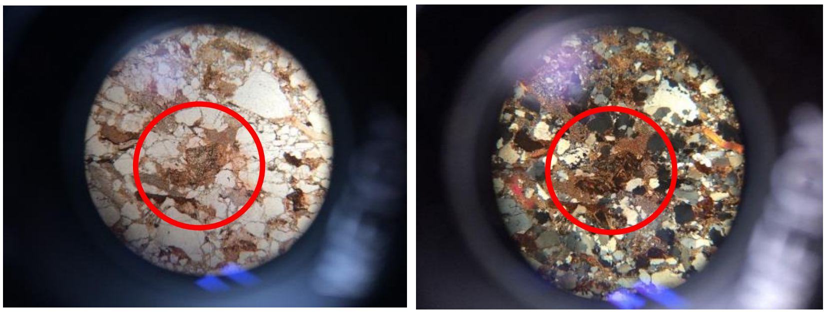

Figure 4.39 Basalt lithic in plain polarised and cross polarised light (circled), sample 36 from drill hole 660 in the Rewanui Formation at a depth of 102.6m.

The unknown lithic category was used for any and all lithics counted, that could not be identified. This was generally due to the size of the lithic being too small. However, the unknown lithic looks similar to a basaltic grain, but the quartz grains within the lithic determined it to be an unknown grain (Figure 4.40). This category was rarely used as the range of grains and minerals was fairly consistent throughout the samples. There were a total of three counted unknown lithics in three different samples. The percentages of these lithics ranged from 0.19% to 2.6%.

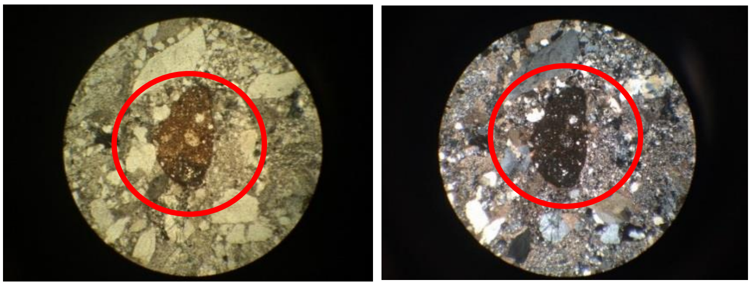

Figure 4.40 Unknown lithic in plain polarised and cross polarised light (circled), sample 45 from drill hole 660 in the Rewanui Formation at a depth of 126.1m.

Opaques were found sporadically throughout most of the point counts. These opaque blobs ranged from very fine to fine sand sized in plain polarised light and cross polarised light (Figure 4.41). They appeared in small percentages, ranging from 0% to 8%, across all of the samples but with a slightly higher appearance in the 12 Mile Beach samples.

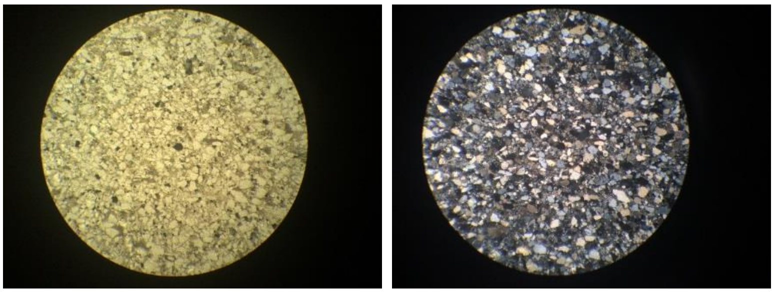

Figure 4.41 Opaques in plain polarised and cross polarised light, sample 54 from drill hole 660 in the Rewanui Formation at a depth of 158.5m.

A matrix component was common in all but a few of the samples. The matrix ranged from mud to very fine grained sand (Figure 4.42). The amount of matrix varied for each sample from 0% to a maximum of 20.6% in one sample. However, the matrix percent was generally low throughout the majority of the samples.

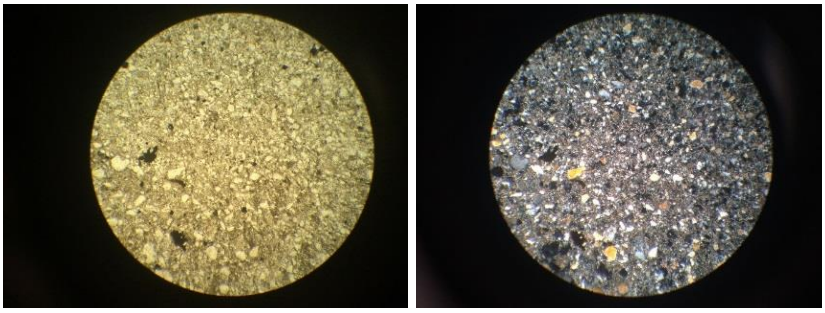

Figure 4.42 Matrix in plain polarised and cross polarised light, sample 58 from drill hole 660 in the Rewanui Formation at a depth of 161.5m.

Organic Fragments were counted on numerous samples and ranged from small fragments to ribbons that cut across the thin section. They appeared brown to black in both plain and crossed polarised light (Figure 4.43). The organic fragment component ranged from 0% to 4.6% throughout the samples.

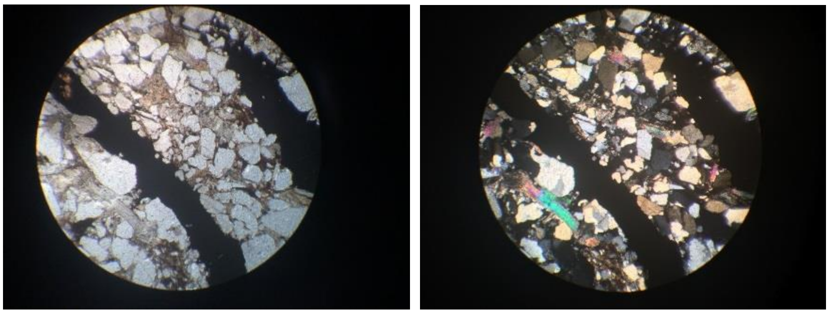

Figure 4.43 Organic material in plain polarised and cross polarised light, sample 94 from drill hole 632 in the Rewanui Formation at a depth of 291m.

4.2.1 Sandstone Point Counts

The point count percentages are graphed below in reference to the north-west versus axial locations. The data was analysed in terms of formation and location but it was determined that the biggest difference in composition of the sandstones was north-west versus the basin axis.

The north-western side of the basin is composed of drill hole 634 and 12 Mile Beach. It is primarily dominated by undulatory quartz with weathered feldspar being the next main constituent (Figure 4.44). There is very little polycrystalline quartz at all with minor biotite and muscovite. 12 Mile Beach samples seem to have the most biotite and muscovite across the samples (Figure 4.44). The other components seem to appear sporadically throughout the samples with no obvious trend.

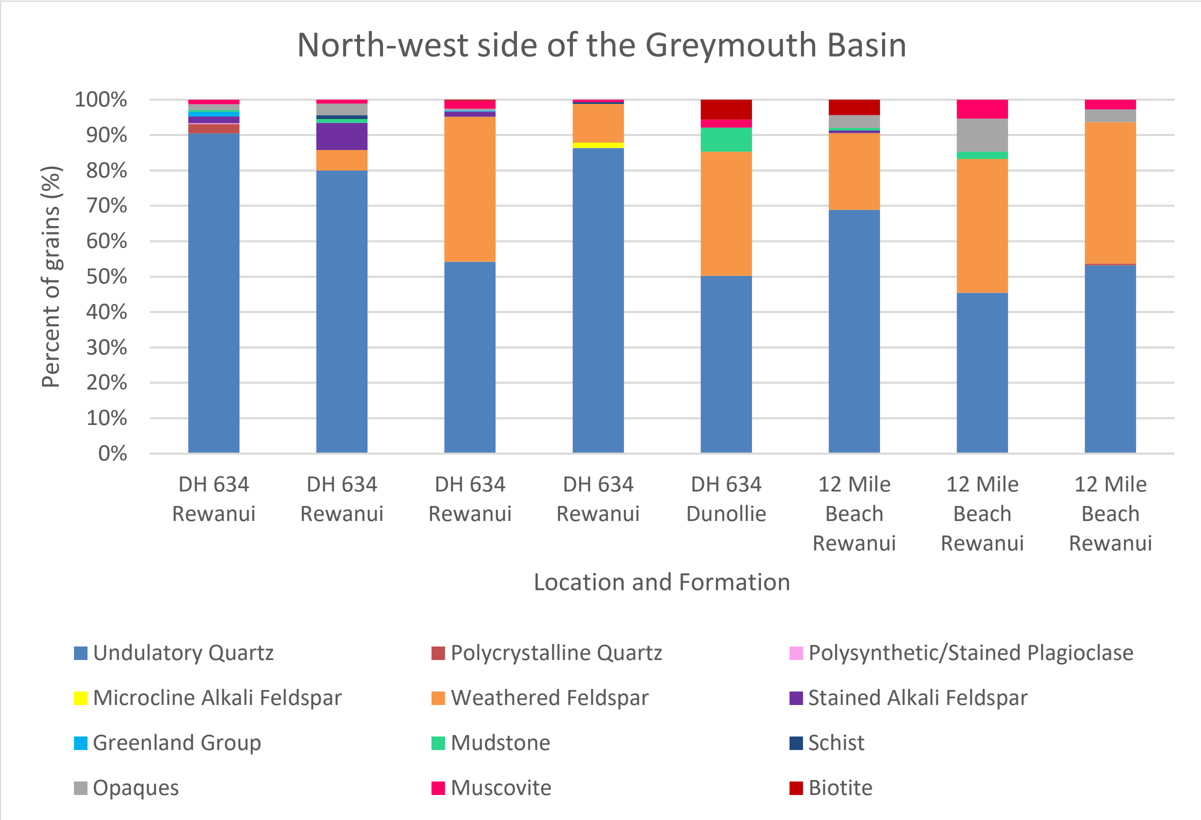

Figure 4.44 Point counts of the sandstones for the north-west side of the Greymouth Basin.

The basin axis is comprised of three drill holes 649, 632 and 660, from the south-west to the north-east. The basin axis is dominated by quartz, especially undulatory quartz, with polycrystalline quartz becoming more dominant as you move from the south-west to the north-east (Figure 4.45). Muscovite and microcline alkali feldspar also increases to the north-west. Weathered feldspar is present across the axis (Figure 4.45). One sample in the Rewanui Formation from drill hole 634 has a substantial mudstone component (Figure 4.45). The other grains seem to appear sporadically throughout the samples, with no real trend (Figure 4.45).

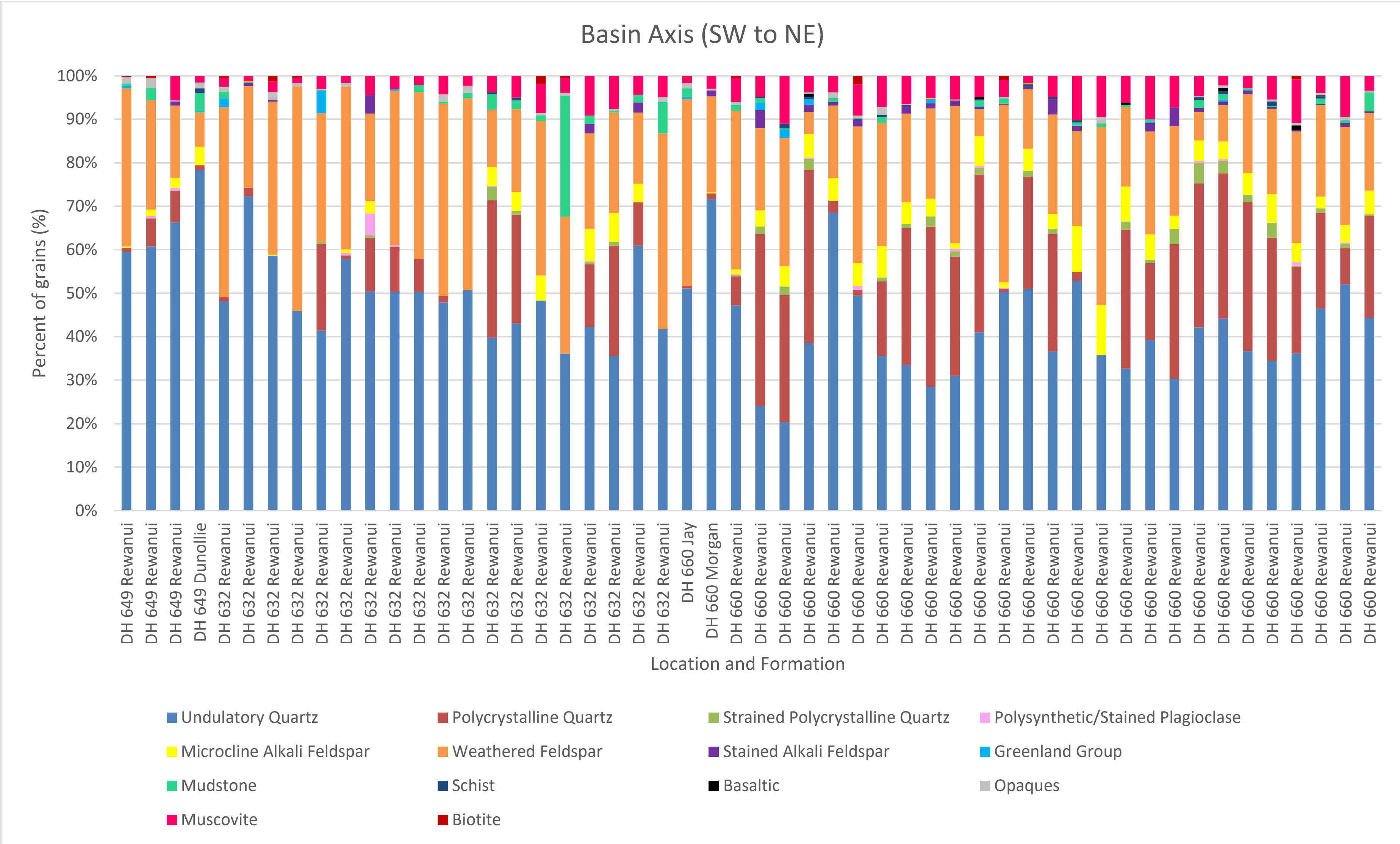

Figure 4.45 Point counts of the sandstones for the axis (SW to NE) of the Greymouth Basin.

4.2.2 Point Count Analysis

The point count results illustrate that quartz was the dominant mineral in the sandstones. Out of the three quartz categories, the dominant grain is undulatory quartz. It is present in all the samples with relatively high percentages. Undulatory quartz was observed in all the formations and all over the basin (Figure 4.44 & 4.45).

Polycrystalline quartz was also consistently a major component of the sandstones, with a significant portion of the overall quartz being polycrystalline. Polycrystalline quartz was observed in most of the finer clastic sediments along the basin axis (Figure 4.45). The Polycrystalline quartz was predominantly found in the basin axis basin form drill hole 649, 632 and 660. There were a few grains found on the western side but not enough to make and substantial conclusions (Figure 4.44).

The strained polycrystalline quartz grains were spotted sporadically throughout the axis samples (Figure 4.45). Strained polycrystalline quartz was non-existent on the north-western side of the basin (Figure 4.44). The strained polycrystalline quartz was only observed in the Rewanui Formation.

Feldspar was the next major constituent of the sandstone samples. Along with quartz it was found in all of the samples across the whole basin (Figure 4.44 & 4.45). Feldspar was separated into four categories; polysynthetic plagioclase, microcline alkali feldspar, stained alkali feldspar and weathered feldspar during point counting. Polysynthetic plagioclase feldspar was not common in any of the sample locations or formations. This was due to the fact that plagioclase feldspar is not as stable at surface temperatures and pressures, and is susceptible to chemical alteration by weathering (Winter, 2010). Most of the plagioclase feldspar identified was substantially weathered. There is no increasing or decreasing trend for polysynthetic plagioclase feldspar illustrated by the point counts.

Microcline feldspar was the most common distinguishable feldspar. Microcline feldspar was found predominantly on the basin axis with some found in drill hole 634 in the north-west (Figure 4.44 & 4.45). No microcline feldspar was found in the sandstones associated with the coarser clastic material at 12 Mile Beach (Figure 4.44). Microcline feldspar increased along the basin axis from the south-west to the north-east, being reasonably consistent stratigraphically throughout drill hole 660 (Figure 4.44 & 4.45). Drill hole 649 does have an increase in microcline feldspar up section in the south-west of the basin.

Stained alkali feldspar was determined by the feldspar staining and observed across the basin and throughout the different formations (Figure 4.44 & 4.45). This category was a minor constituent of the overall feldspar component with a slight increase across the axis from south-west to north-east.

Unidentifiable feldspars were categorised as weathered feldspars and most likely consisted predominantly but not exclusively of plagioclase feldspar remnants (Figure 4.33). The majority of the feldspar component was dedicated to this category due to the weathering. This category did not show any major changes throughout formations or location (Figure 4.44 & 4.45). However, it does illustrate the amount of weathering the samples were subjected to.

The extremely weathered feldspars were distinguished from matrix and Greenland Group lithics predominantly by shape. The extremely weathered feldspars still maintained a sub-angular to sub-rounded shape (Figure 4.33). Matrix had no defined shape and was generally very irregular. Greenland group lithics were obvious to spot, being very fine grained, sub-rounded to rounded, with a fabric (Figure 4.36).

Greenland Group lithics were found sporadically throughout formations and across the basin. The amount of Greenland Group lithics was generally minor with the largest occurrence being in the Rewanui Formation from drill hole 632. The Greenland Group lithics were located predominantly along the basin axis. However, there were a few occurrences in the north-west. These lithics were predominantly found in the Rewanui Formation but were present in the Jay and Dunollie Formations as well.

Mudstone lithics were found sporadically throughout the samples (Figure 4.44 & 4.45). Samples from the Jay, Rewanui and Dunollie Formations had small amounts of mudstone lithics. There were no trends observed, but there was one sample that had an unusually high mudstone component. This sample came from the Rewanui

Formation in drill hole 632. This location in the centre of the basin and had more likely been influenced by lacustrine facies.

Muscovite was found across the basin within all of the clastic formations but more dominant along the basin axis than the north-western side of the basin (Figure 4.44 & 4.45). The muscovite seems to increase in the Rewanui Formation predominantly on the eastern side of the basin in the Rewanui Formation. The muscovite is consistent throughout the formations with the exception of the odd sample.

Biotite was a minor constituent across the sandstone samples (Figure 4.44 & 4.45). It appeared across the basin and in all of the formations apart from the Morgan Formation. The highest concentration of biotite was found in a Dunollie Formation sample, from drill hole 634 in the north west of the basin. There does not appear to be any trend in the biotite data.

Schist lithics were only observed in small quantities throughout the samples (Figure 4.44 & 4.45). The schist lithics were only found along the basin axis with an increase towards the north-east. The schist lithics were only observed in the Rewanui and Dunollie Formation.

Basaltic lithics are rare and were only identified in the north-eastern side of the basin axis in the Rewanui Formation (Figure 4.45).

Opaques were a minor constituent constant throughout all of the samples and present in all of the formations and at all locations (Figure 4.44 & 4.45).

Only three unknown lithics were observed across the basin. All three were observed in the north-eastern side of the basin axis in the Rewanui Formation. The three unknown lithics were excluded from the final results, due to the very small number and the fact that due to the nature of the lithic being unknown, it does not provide any relevant information to determine provenance.

Organic fragments were very minor and excluded from the final results, as they do not help in determining the provenance. The organic fragments were identified throughout all the formations and across the entire basin.

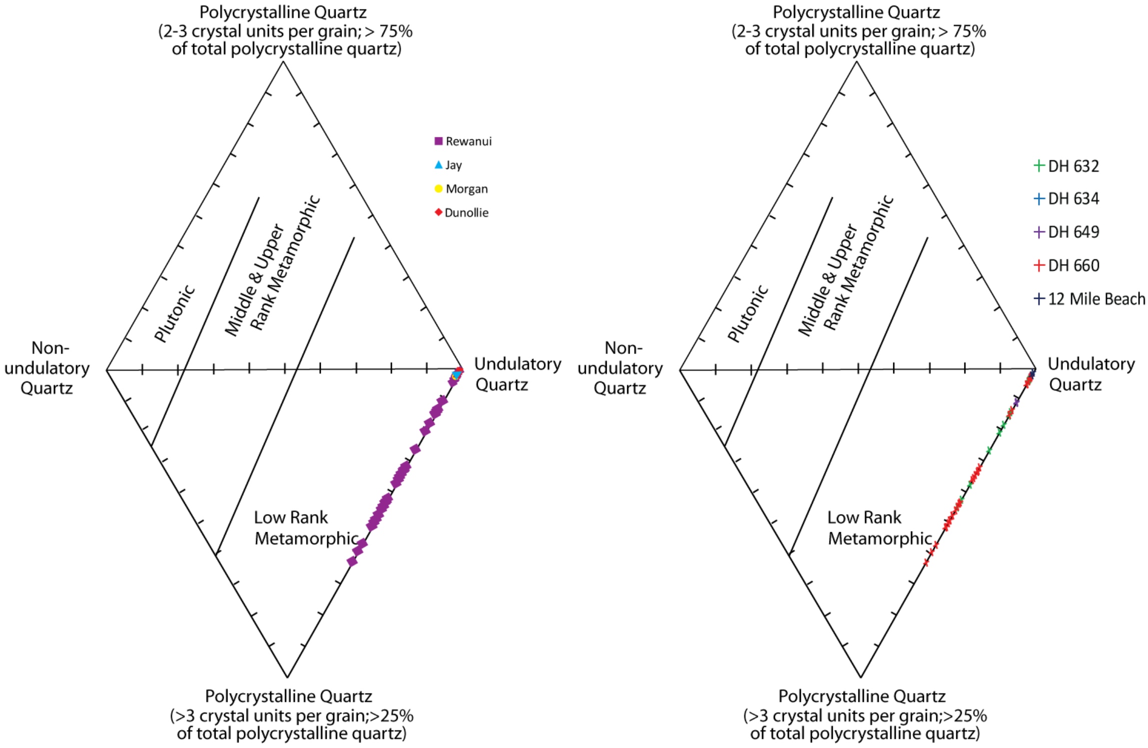

Figure 4.46 Provenance of quartz source by quartz type (Basu et al., 1975; Basu, 1985), shown by formation and drill hole location.

The different types of quartz can determine the type of source rock (Pettijohn et al., 1972; Basu et al., 1975; Basu, 1985). The three types of quartz were plotted according to Basu et al., (1975), to illustrate the source of the quartz in the sandstones. The results show that the Rewanui Formation had the biggest variation in quartz types, with a range of undulatory and polycrystalline quartz dominating (Figure 4.46). No straight extinction quartz was observed during point counts with undulatory quartz being the overall dominant quartz type. The north-western side of the basin, 12 Mile Beach and drill hole 634 were dominated by undulatory quartz, with little to no polycrystalline influence (Figure 4.46). The basin axis (DH 649, 632 & 660) shows an increase from south-west to north-east (Figure 4.46). Polycrystalline quartz is the most dominant in the north-eastern side of the basin axis (DH 660) (Figure 4.46). This infers only a low rank metamorphic source in the north-west and the basin axis with a secondary higher grade metamorphic source influencing the basin axis (Pettijohn et al., 1972; Basu et al., 1975; Basu, 1985). However, undulatory quartz is not exclusive to only low rank metamorphic sources, but plutons subjected to deformation can contain undulatory quartz as well (Basu et al., 1975).

4.2.3 Sandstone Tectonic Setting

The relationship between sandstone compositions and tectonic setting was recognized through the work of Dickinson and Suczek (1979), and Dickinson et al. (1983). They showed that by plotting the detrital framework categories of sandstone suites on a (Quartz, Feldspar, Lithics) (QFL) ternary diagram resulted in information about the tectonic setting of the depositional basins and their associated provenance (Dickinson et al., 1983). The QFL diagram is divided into three main categories, with three sub-fields each. However, the Recycled Orogen field is the exception. The three main fields are representative of three different types of tectonic regime, continental blocks, magmatic arcs, and recycled orogens (Dickinson et al., 1983). There is also a more specific QmFLt diagram which is similar to the QFL diagram, except that it plots exclusively monocrystalline quartz (Qm), and total polycrystalline lithics (Lt) (Dickinson et al., 1983). Dickinson and Suczek (1979) established that sandstone suites from different kinds of depositional basins are a function of provenance types controlled by plate 3 tectonics. In general, sediments derived from continental interiors and deposited within intracratonic basins or along passive margins, are rich in detrital quartz and poor in lithic fragments, especially volcanic lithics. Clastic sediment derived from recycled orogens is commonly more felsic than craton-derived sediment, even though the depositional setting on passive margins may be the same. Clastic sediments derived from volcanic arcs (continental or oceanic) are typically poor in detrital quartz and rich in volcanic lithics.

The point count data was applied to these categories to determine tectonic setting of the Paparoa Coal Measures (Dickinson & Suczek, 1979; Dickinson et al., 1983). The QFL graph was plotted first with the majority of the sandstone samples coming from the Rewanui Formation.

The QFL diagram (Figure 4.47) shows that the majority of the sandstones fall in the transitional continental area on the graph. There are a few outliers that fall inside recycled orogeny, dissected arc and basement uplift. The results show a dominant trend along the transitional continental section of the graph (Figure 4.47). This indicates that the Greymouth Basin is a continental rift basin, which is consistent the stratigraphic and facies interpretations made in the previous chapter along with previous interpretations (Gage, 1952; Nathan, 1978; Newman, 1985; Laird &

Bradshaw, 2003; Strogan et al., 2017). This graph determines lithics to be of volcanic origin. This however, does not apply here as the majority of the lithics are of sedimentological origin. The slight recycled orogenic component would most likely be associated with the Greenland Group. The few samples falling into the dissected arc section, is purely a result of the categorisation of lithics. There are a few basaltic lithics found throughout the samples but these were rare with the lithics consisting predominantly of Greenland Group and mudstone.

The QmFLt diagram is more specific than the QFL diagram, as it plots exclusively monocrystalline quartz (Qm), and total polycrystalline lithics (Lt) (Figure 4.47) (Dickinson et al., 1983).

The QmFLt plot results are different from the more simplified QFL plot. The result of the graph shows that there is a mixture of different tectonic settings responsible for these sediments. There are two distinct trends in the data, one along the transitional continental and the other along the mixed/dissected arc division (Figure 4.47). There are also a few outliers plotting in the transitional arc and transitional recycled.

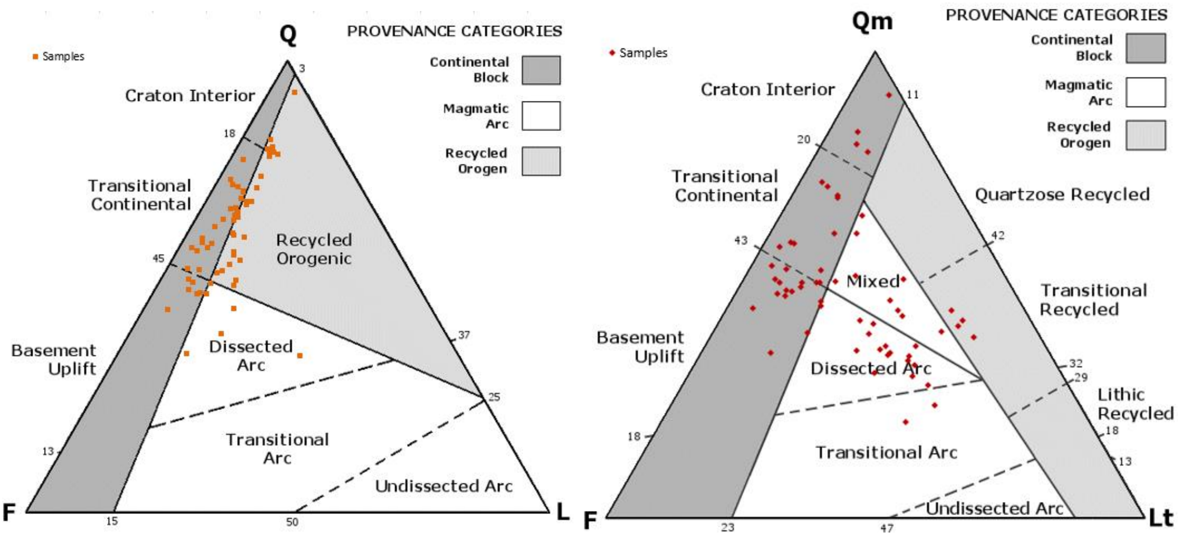

Figure 4.47 QFL and QmFLt tectonic setting diagrams (Dickinson & Suczek, 1979), and Dickinson et al., 1983).

This diagram also has a categorisation problem as it too, is assuming the lithics are volcanic. However, this is not the case resulting in a mixed transitional continental and transitional recycled tectonic setting. This conclusion supports the previous tectonic setting conclusion while hinting at a basement rock source.

The data suggests that there is one dominant tectonic setting at work. The transitional continental is consistent with previous interpretations of the development of the basin (Gage, 1952; Nathan, 1978; Newman, 1985; Laird & Bradshaw 2003; Strogan et al 2017). The transitional recycled tectonic setting is a result of a categorisation issue with the type of lithic. Concluding a transitional continental tectonic rift basin environment, during the deposition of the Paparoa Coal Measures.

4.3 Mudstone Geochemical Analysis and Provenance

The geochemical analysis of the mudstones was utilised to determine the parent or source rock for the sediments. The trace elements and REE's (Rare Earth Elements) were measured to determine the type of source rock that the mudstones are derived from (Potter et al., 2005; Arribas et al., 2007). The mudstone geochemical analysis consisted of the same major and trace element components as the rest of the samples. Major elements analysed were; SiO_2, TiO_2, Al_2O_3, Fe_2O_3, MnO, MgO, CaO, Na_2O, K_2O and P_2O_5. Trace elements also analysed were of As, Ba, Ce, Cr, Cu, Ga, La, Nb, Ni, Pb, Rb, Sc, Sr, Th, U, V, Y, Zn and Zr. The trace element analysis of the mudstones was going to include plots such as Th/Sc against Sc, and Cr/Th against Sc/Th as indicators of the proportions of felsic and mafic source rocks (Condie & Wronkiewicz, 1990; McLennan et al., 1990, McLennan & Taylor, 1991). This however, was decided against as the two possible sources for the lacustrine Waiomo and Goldlight Formations, Greenland Group and a granitic source are felsic. It was determined that these plots would not provide any useful results.

Geochemical analysis was used to help determine the source of the sediments comprising the lacustrine deposits (Cullers et al.,1987; Condie, 1991; Potter et al., 2005; Arribas et al., 2007). The trace element concentrations were compared to the most dominant source of sediments on the Paparoa Coal Measures (Cullers et al.,1987; Condie, 1991; Potter et al., 2005; Arribas et al., 2007). The results were normalised to the Greenland Group. The Greenland Group data set used to normalise was from Petlab (Strong et al., 2016). The Greenland Group data set comprised of over 450 analysed samples. This data was then averaged over each element to determine the average concentration of each trace element. The trace element profile of the mudstone will illustrate if the Waiomo or Goldlight Formations, had received any input outside of the Greenland Group.

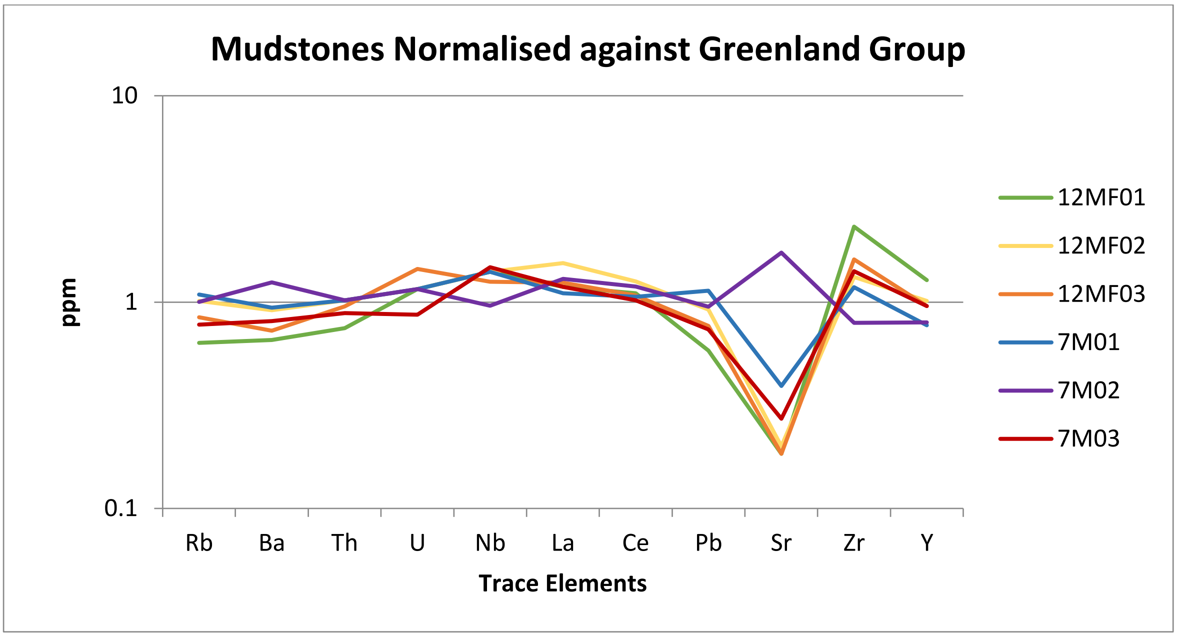

Figure 4.48 Waiomo and Goldlight Formations trace element concentrations normalised against Greenland Group. Greenland Group data from Petlab (Strong et al., 2016).

The results are reasonably consistent with one dramatic outlier, sample 7M02. This sample has a higher barium (Ba) and strontium (Sr), with a lower zirconium (Zr) concentration than the other samples (Figure 4.48). The remaining samples had a subtle drop in barium (Ba) and strontium (Sr) and an increase in zirconium (Zr) (Figure 4.48). The last significant difference between the samples is the difference in concentrations of zirconium (Zr). Sample 7M02 has a lower concentration than the other samples, which contain a higher concentration than the normalised Greenland Group.

Sample 7M02 comes from the middle of the Goldlight Formation. This could be a reason for the sample to be less weathered, as both barium (Ba) and strontium (Sr) are very mobile elements susceptible to weathering (Middelburg et al., 1988; Cullers et al.,1987; Condie, 1991; Potter et al., 2005; Arribas et al., 2007). The other mudstone samples are quite consistent with a significant drop in concentration of strontium (Sr), which could be a consequence of weathering (Middelburg et al., 1988). However, the subtle drop in barium (Ba) and strontium (Sr) could also indicate the presence of another source (Figure 4.48). The higher concentrations of zirconium (Zr) indicate that this might be the case as zirconium (Zr) is high in granites (Winter, 2010). Therefore it is reasonable to infer that there was a granitic influence with a dominant Greenland Group source recorded in the mudstones.

The relevance of this information is that it provides supporting evidence and data for the provenance analysis of the conglomerates and sandstone data. Therefore, substantiating any claims or interpretations made in terms of provenance of the Paparoa Coal Measures in the Greymouth Basin.

4.4 Conglomerate Provenance

Clast counts taken from the conglomerates across the basin support the previous interpretations with the conglomerates comprising primarily of Greenland Group (Gage, 1952; Nathan, 1975; Newman, 1985; Newman & Newman, 1992; Ward, 1997). The Greenland Group was consistently the predominant clast type in every clast count, with the exception of the Morgan Volcanics. The Greenland Group influence is sourced from the basement rock which is prevalent throughout the West Coast region. This result was not unexpected as this sediment source for the coarse clastic sediments has been confirmed by multiple investigations (Gage, 1952; Nathan, 1975; Newman, 1985; Newman & Newman, 1992; Ward, 1997).

The large crystalline quartz clast component is a constant, like the Greenland Group clasts. The quartz clasts are likely fragments of quartz veins that lie within the Greenland Group. This explains why the quartz fragments are consistent along with the Greenland Group as the quartz source is the Greenland Group.

The clast counts did reveal some interesting trends with the occurrence of aplite clasts in the lower conglomerates (Jay and Morgan Formation) increasing in appearance up section, until fading out in the base of the Rewanui Formation with the introduction of the granitic clasts. Aplite is formed from residual eutectic granitic liquids and represents the final crystallization products of magma (Winter, 2010). The aplite is thought to be the precursor to unroofing the granitic body. The clast counts also indicate the appearance of hornfels clasts at the same time as the aplite.

Hornfels clasts are formed by contact metamorphism and are likely the result of the contact metamorphism areole around the intruded granitic body, into the Greenland Group. Therefore, the protolith of the hornfels clasts is likely the Greenland Group basement as a consequence of the pluton intruding the country rock. The hornfels clasts do not fade out with the introduction of the granitic clast in the Rewanui Formation compared to the aplite. This makes sense as the aplite is pegmatite and will not be as extensive as the surrounding areole of hornfels.

The granitic clasts within the younger conglomerates (Rewanui and Dunollie Formations) provide irrefutable evidence of a granitic influence on the coarser clastic sediments in the north-west with pebble to boulders of granite observed. These clasts only occur in the north-west as they were only encountered and observed at the 12 Mile beach outcrop and in core form drill hole 634. The granitic source of the clasts was determined to be neither older, Barrytown granite part of the Middle-Devonian Karamea Suite, or the younger Buckland granite from the Late Cretaceous Rahu Suite (Tulloch, 1983; Tulloch & Brathwaite, 1986; Muir et al., 1994; Nunweek, 2001). Petrographic analysis determined that the granitic clasts were weathered with high clay content and rare plagioclase feldspars. Comparing thin section analysis to thin section and hand sample analysis of both the Rahu and Karamea Suites, the samples were more similar to the Rahu Suite. Geochemical analysis was used with the major element analysis, showing an indication towards the Karamea Suite as a source. Two of the samples indicated the same major element composition as the Karamea Suite, but the other samples show an unusually high concentration of potassium (K) relative to sodium (Na) and calcium (Ca). The cause of the high concentrations of potassium (K) was concluded to be due to weathering. The major element analysis contradicts the hand sample and petrographic analysis. The trace element analysis was also contradictory as it also suggested the Karamea Suite as the likely source, as the trace element profiles were the closest, even with the similarity with the Rahu Suite.

However, based on the geochemistry, the granitic samples have been concluded to have come from neither the Barrytown nor the Buckland granites, but from an A-type granite inferred offshore, on the footwall block (Andrew Tulloch, pers. comm. 2017). A-type granites typically have low barium (Br) and strontium (Sr) which are evident in the Paparoa Coal Measures granitic clasts (Figure 4.20). A-type granites are also commonly associated with rift basins, which fits with the concluded tectonic setting of the Greymouth Basin. There is also evidence of A-type granites on the West Coast and evidence of granitic basement offshore (Tulloch et al., 1992; Andrew Tulloch, pers. comm. 2017). The Kongahu-1 well is the closest offshore well to the Greymouth Basin that intercepts a deformed Cretaceous aged granitic basement (Wiltshire, 1984).

Basaltic clasts appeared in the Jay, Morgan and Rewanui Formation. There was only one location in which the Jay Formation had basalt clasts within it, and that was in drill hole 660 in the north-eastern corner of the basin. In the Rewanui Formation, predominantly on the north-western side on the basin, basaltic clasts were scattered throughout the coarse conglomerates as fine to medium pebbles. These clasts were subjected to geochemical analysis that determined them to be basaltic andesite and andesite. The presence of these clasts in the western coarse sediments suggests that there was some volcanism on this side of the basin. This is supported with other investigations identifying tuff and lavas within the Paparoa Coal Measures (Gage, 1952; Laird, 1968; Bishop, 1992).

The occurrence of basaltic clasts in the Morgan was restricted to a small area near the Roa Mine. The Morgan Volcanics is comprised of basaltic volcanics with igneous clast conglomerate, basaltic lava flows and pillow lavas (Gage, 1952; Newman, 1985; Ward, 1997). The occurrence of these sediments are the main evidence for volcanism on the east side of the basin, along with the lava flows encountered by drill hole. The eastern side of the basins volcanism has been accepted since Gage first described the Morgan Volcanics in 1952. However, the basaltic clasts identified on the western side of the basin, provides more supporting evidence of volcanism on the western side of the basin. Whereas previously, there has only been minor evidence and speculation of volcanism on this side of the basin (Gage, 1952; Nathan, 1978; Newman, 1985).

Clasts counts illustrate that the western side of the basin is dominated by a Greenland Group source with a substantial granitic source influence. The appearance of aplite and hornfels in the lower conglomerates illustrate the evolution of the granitic source with the unroofing of the granitic body that intruded the Greenland Group.

4.5 Sandstone Provenance

The eastern side of the Greymouth Basin is dominated by sandstone and mudstones. The controversy surrounding the eastern side of the basin is the source of the finer clastic sediments. Newman believed that a second granitic source was the origin of the quartz and feldspar sandstone sediments (Newman, 1985). Since Newman's conclusions, further research has also come to the same conclusion, that the eastern side of the basin was dominated by a north-eastern axial sandy fluvial system that carried and deposited granite derived detritus (Newman, 1985; Ward, 1997).

Sandstone dominated the basin axis with most of the sandstone samples coming from that side. There were however, plenty of sandstone beds intercepted by the drill core along the north-western side of the basin and at drill hole 634 and 12 Mile Beach.

The sandstone point counts revealed that the sandstone is predominantly composed of quartz, feldspar and weathered feldspar. Most of the feldspar component was weathered to varying degrees. The weathered feldspar was composed predominantly of plagioclase feldspar with minor to extreme weathering. The majority of the sandstone samples came from the Rewanui Formation due to core accessibility.

The quartz component of the sandstones was divided into three categories undulose, polycrystalline and strained polycrystalline. Undulosity in quartz from low rank metamorphic rocks is sufficiently different from that in pluton-derived quartz, to be useful in provenance interpretation (Pettijohn et al., 1972; Basu et al., 1975; Basu, 1985). Polycrystalline quartz can be found in both igneous and metamorphic terranes, but are very rare in igneous and always indicates a degree of strain (Pettijohn et al., 1972; Basu et al., 1975; Basu, 1985). Strained polycrystalline quartz is gneissic polycrystalline quartz as it more finely crystalline and subjected to higher degrees of strain (Pettijohn et al., 1972; Basu et al., 1975; Basu, 1985). The percentage of these categories determines the likely source of the quartz grains (Pettijohn et al., 1972; Basu eta al., 1975; Basu, 1985).

All the quartz counted had some form of undulatory extinction which ranged from weak to strong. No straight extinction quartz was observed in thin sections. The undulatory quartz grains indicate a low rank metamorphic source, like the Greenland Group. However, the large grainsize of the undulatory quartz grains is too large for the predominantly fine grained metasandstone Greenland Group, and the volume of quartz is too high to have come from vein quartz. Therefore, a coarser grained quartz source is indicated. The lack of straight extinction quartz observed does not discount the possibility of a plutonic influence (Basu et al., 1975; Basu, 1985).

Plutonic quartz typically has no undulatory extinction however, deformed granitic bodies may do. Strain and heat needs to be applied to the quartz grains to deform them to show undulatory extinction (Winter, 2010). The proposed source of the granitic born sediments, is either the Middle to Late Devonian Karamea Suite (Barrytown granite), or the Late Cretaceous Rahu suite (Buckland granite) (Tulloch 1973; Muir et al., 1994; Nunweek, 2001). The Karamea Suite is older than the Late Cretaceous rifting that opened the Tasman Sea and therefore, would have been subjected to more deformation during its lifetime than the Rahu Suite. This would allow some of the plutonic quartz grains to exhibit some undulatory extinction. However, the Rahu Suite has been subjected to some deformation to, as it is associated with the opening of the Tasman Sea and separation from Gondwana (Muir et al.. 1994; Mortimer et al., 2014). This would explain the lack in plutonic non-undulatory quartz, and provide supporting evidence for either the Karamea (Barrytown granite) or Rahu (Buckland granite) Suite being the granitic source of the Paparoa Coal Measures. Therefore, some of the undulatory quartz grains can infer a plutonic source as well as a low grade metamorphic source.

The undulatory quartz on the north-western side of the basin is likely sourced from a, slightly deformed, granitic source. The proposed A-type granite offshore is associated with the rifting and formation of the Greymouth Basin. This tectonic regime is just as likely to have deformed the A-type granite as the Rahu Suite. Therefore, being the granitic source for the conglomerates and sandstones on the north-western side of the fault.

Polycrystalline quartz and strained polycrystalline quartz are an indication of a high grade metamorphic gneissic influence in the sandstones (Pettijohn et al., 1972; Basu, Young, Suttner, James, & Mack, 1975; Basu, 1985). The Muscovite and schist lithics are also an indication of a higher grade metamorphic source than the Greenland Group. These grains are predominantly found along the basin axis and are concentrated to the north-east of the basin axis. Therefore, the consistent influence of the polycrystalline quartz, muscovite and schist lithics is likely from axial drainage from the north-east. The high grade metamorphic source is likely the Charleston Metamorphic Group which lies to the north of the basin (Figure 4.16). This would explain the polycrystalline quartz, muscovite and schist lithic grains without having a directly local high grade metamorphic source.

Greenland Group lithics were predominantly found in the centre and in the east of the basin. This supports previous conclusions of a Greenland Group source to the east. The few occurrences of Greenland Group lithics in the south-west can be attributed to axial drainage.

The lack of Greenland Group lithics is a slight concern, considering the Greenland Group is the dominant source for the Greymouth Basin. There is a possibility that some of the Greenland Group lithics were misidentified as weathered feldspar or matrix. However, this is unlikely as every step was taken to identify every grain correctly. The Greenland Group lithics identified were obvious and unmistakable, with a fine grained fabric and sub-rounded to rounded grainsize. The lack of Greenland Group lithics could be attributed to the fine grainsize and weathering. The axial drainage depositional facies incorporated mires and long sediment transportation times. Coal and mire producing environments are considered relatively acidic which would cause the Greenland Group lithics to be subjected to temporary storage in acidic flood plains and alter to mud (Bennett, Rogers, Choi, & Hiebert, 2001).

The point counting data and quartz grain analysis suggest a plutonic source, likely the A-type granite and the Greenland Group source for the north-western derived sandstones. The basin axis sandstones were derived from Greenland Group, a plutonic source (likely Buckland granite, due to direction of axial drainage) and the

Charleston Metamorphic Group from the north-east. These results confirm Newman, 1985's deduction of a plutonic source in the east as well as the west.

4.6 Mudstone provenance

The mudstone geochemical analysis of the Waiomo and Goldlight Formations was conducted to determine if there were any unusual influences on the sediment being deposited in the lacustrine facies deposits. The results were normalised to Greenland Group to illustrate any outside influence on the sediment.

The results were generally consistent with the Greenland Group with only one sample showing a higher strontium (Sr) and lower zirconium (Zr) concentration than the others. The reaming samples all showed low strontium (Sr) and high zirconium (Zr) concentrations, indicating a probable secondary plutonic source with the dominant Greenland Group source.

The mudstone geochemical analysis shows that the predominant sediment source is the Greenland Group with some granitic influence.

4.7 Conclusion

The results show that the Paparoa Coal Measures in the Greymouth Basin was fed by two principal sediment sources (Gage, 1952; Nathan, 1978; Newman, 1985; Newman & Newman, 1992; Ward, 1997). The north-eastern axial sandy fluvial system carried granite-derived detritus with Greenland Group and Charleston Metamorphic Group influence (polycrystalline quartz and muscovite) into the basin. Whereas, the north-western basin margin supplied sand and gravel derived from Paleozoic Greenland Group basement and an A-type granite.

The provenance analysis of the clasts, sandstones and mudstones conclude that there are two dominant sediment sources for the Paparoa Coal Measures, Greenland Group and a plutonic source. A Greenland Group and A-type granite source to the north-west and a Greenland Group and granitic source to the north-east, that entered the basin by axial drainage with Charleston Metamorphic Group influence. The results solve the controversy between Gage and Newman regarding sediment sources of the Paparoa Coal Measures. This provides a better understanding of the formation of the Paparoa Coal measures and the Greymouth Basin.

Chapter 5 Morgan Volcanic Conglomerate

The Morgan Volcanics were first mentioned by Gage in 1952 and are located only in the north-east of the Greymouth Basin, near Roa Mine. The Morgan Volcanics have been recognised in previous studies on the basin, but no real analysis has been undertaken on them (Gage, 1952; Laird, 1968; Nathan, 1978; Newman, 1985; Bishop, 1992). The Morgan Volcanic conglomerate is comprised of Upper Cretaceous basaltic volcanics and other clastic sediments, consisting of sub-rounded pebbles to boulders. The Morgan Formation also includes interbedded basaltic lava flows, 4ft to 50ft thick (Gage, 1952; Nathan, 1978; Newman, 1985; Bishop, 1992). The Morgan Volcanic conglomerates thicken rapidly eastwards towards the Mount Buckley Fault Zone, where they abruptly terminate, with little igneous material being found east of the zone (Gage, 1952; Laird, 1968). The large thickness and limited lateral extent, is controlled by a sharp local depression immediately to the west of the active Mt Buckley Fault Zone, and close to the centre of active volcanism (Gage, 1952; Laird, 1968).

Drilling by Shell BP Todd Oil Services Ltd. at the Arahura River discovered a basalt flow, within the Paparoa Coal Measures (Laird, 1968; Newman, 1985; Bishop, 1992). This can be correlated with reasonable confidence with the Morgan basaltic volcanics at Roa. The basalt occurs on the eastern side of the basin, and is probably derived from a local volcanic centre, similar to the Morgan Volcanics at Roa (Laird, 1968; Nathan, 1978; Newman, 1985). The Paparoa Coal Measures are intruded into, and interbedded with tuffs and lavas (Gage, 1952; Laird, 1968; Bishop, 1992). Thin pyroclastic beds are also common in drill core and exposures on the western side of the field, and geochemical analysis indicates a relatively acidic composition compared with the Morgan Volcanics (Newman, 1985).

The Morgan Volcanic conglomerate was found approximately 4 km up Paparoa Creek, next to Blackball on the eastern edge of the Paparoa Basin. Three clast counts were conducted at three locations within the lithology. Due to the location of the outcrop, neither GPS nor cell phone reception was available. Therefore, the locations have been approximated using Google Earth.

The Morgan Volcanic conglomerate will be investigated with respect to; outcrop with clast counts and standard outcrop observations, petrographic analysis and geochemical analysis. The standard outcrop observations of structure, textures and compositions will be undertaken at outcrop. The petrographic analysis will provide a more detailed analysis of the textures and composition of the clasts. The geochemical analysis will provide another level of detail, with major and trace element concentrations determined.

The analysis of these clasts within the Morgan Volcanic conglomerate will provide information on the evolution and tectonic setting these clasts formed in, and that of the Greymouth Basin.

5.1 Clasts Encountered

The Morgan Volcanic conglomerate consisted of four clast categories that were identified during the clast counts, green and brown sandstone, quartz, mudstone and basalt. These clasts ranged in size from medium pebble to cobble and colour (Figure 5.1). The initial categorisation of the clasts in the field was based on colour. This has been adjusted after thin section analysis and a basalt category is used to encompass them all.

Figure 5.1 Basalt clasts in outcrop from the Morgan igneous conglomerate, found in the Paparoa Creek, 42°21'49.53S 171°22'18.25E.

Green and Brown Metasandstone

The green and brown metasandstone clasts vary in size from fine pebble to cobble, very well indurated, sub to well-rounded, and vary from silty very fine sand to medium grained sandstone.

Thin sections show very fine-grained silt to sandstone with a slight fabric. Composition varies slightly throughout the samples, with the percentage of the minerals changing marginally with each sample. Components consist of quartz ~40%, ~10-20% feldspar, muscovite ~1-3%, chlorite ~5-7% and very fine indistinguishable matrix ~ 30-44%. Some minor iron staining is observed in a few of the samples.

These clasts are identified as being derived from the Greenland Group basement rock. The Greenland Group is the local basement rock for the West Coast of New Zealand, and is a very distinctive green meta-sedimentary rock (Laird, 1972; Laird, 1974; Nathan, 1978). However, there is some slight variation in colour as Greenland Group can be brownish in appearance. Every conglomerate formation in the Paparoa Coal Measures has a component of these basement rock clasts within it. It is brown to green, highly indurated sandstone and mudstone greywacke and argillite (Laird, 1972; Laird, 1974; Nathan, 1978). Petrographic analysis shows an abundance of quartz, relative to feldspar in the clastic constituents (Laird 1972; Laird, 1974).

Quartz

The quartz clasts appear milky white to clear, sub-rounded to sub angular, granule to fine pebble clasts in the Morgan Volcanic conglomerate. These vein fragments are commonly coarsely crystalline, with a glassy appearance in hand sample. These clasts are determined to be fragments of large quartz veins, due to the coarse crystalline nature of the clasts.

The source of these quartz clasts is most likely the Greenland Group. The Greenland Group basement has extensive coarse quartz and pegmatite veins throughout the rock (Gage, 1952; Laird, 1972; Laird, 1974).

Basalt

The conglomerate was predominantly comprised of these basaltic clasts (Figure 5.1). The basaltic clasts ranged from a pale green-grey clast to a rusty red colour, as well as the standard dark grey black basalt clast. The clasts ranged in size from a medium pebble to cobble sized clast, that were sub-rounded to well-rounded and speckled with milky white amygdaloids.

Amygdaloids are vesicles that have been filled in with a secondary mineral, long after the flow cooled (Figure 5.3) (Winter, 2010). The secondary minerals are commonly white composed of quartz, calcite, or zeolite.

Thin section analysis shows a porphyritic texture with large phenocrysts and a fine crystalline groundmass. Slightly altered ortho and clino-pyroxenes were common as the dominant phenocryst, distinguished by habit, extinction and birefringence, supported by a few remaining unaltered specimens, ranging from ~ 20 to 35% across the samples (Figure 5.2) (Phillips & Griffin, 1981; Deer et al., 1992). The odd plagioclase tabular crystal was observed as well, determined by clear in plain polarised light, habit, low first order birefringence, and most distinguishing polysynthetic twinning, ranging from ~0 to 10 % (Phillips & Griffin, 1981; Deer et al., 1992). Thin sections show a variety of different coloured ground mass ranging from typical dark grey to red. The groundmass comprised predominantly by tabular microlites, most likely feldspars, ranging ~ 40 to 55% across the samples.

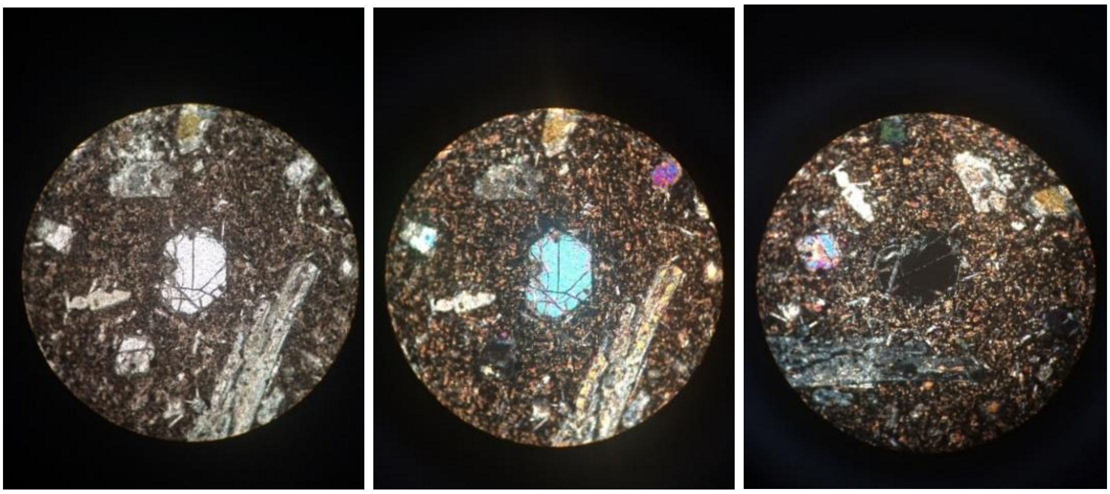

Figure 5.2 Sample BB01, showing pyroxene in plain and cross polarised light.

The amygdaloids were primarily filled with calcite as the hand sample effervesced when Hydrochloric Acid (HCL) was applied. Calcite is also quite distinguishable in thin section with its pearly, high birefringence (Phillips & Griffin, 1981; Deer et al., 1992). The amygdaloids were also filled with a zeolite mineral determined to be Thomsonite (Figure 5.3). The determination of Thomsonite was due to the following diagnostic properties; fibrous, acicular, greenish in plain polarised light, a straight extinction along the prism and a mid to high first order birefringence, ranging from ~0 to 10% across the samples (Phillips & Griffin, 1981; Deer et al., 1992).

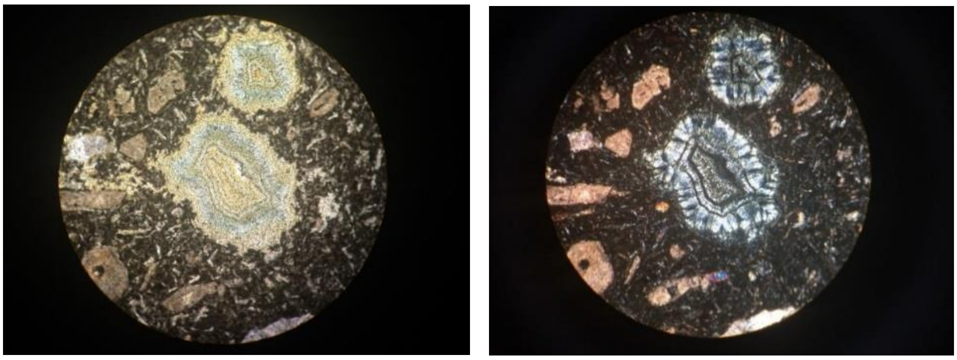

Figure 5.3 Sample BB04, showing amygdales of Thomsonite in plain and cross polarised light.

The thin section textures show that the basalt clasts had two stages of cooling evident by the larger phenocrysts and the smaller microlites in the groundmass (Figure 5.2) (Winter, 2010). The first slower stage of cooling allowed for the growth of the larger phenocrysts, and a second stage of rapid cooling resulted in the smaller microlites (Winter, 2010). This supports the conclusion of the clasts being extrusive basalts as the textures are associated with basaltic rocks (Winter, 2010).

The filled vesicles (amygdaloids) are the second dominant feature in thin section (Figure 5.3). The filled vesicles suggest that there was some saturated calcium rich fluid flowing around the clasts during burial. The presence of zeolite mineral Thomsonite also suggests fluid mobilisation after burial (Winter, 2010). The amygdaloids are caused by secondary mineralisation because of burial and diagenesis (Winter, 2010).

Mudstone

The mudstone clasts encountered were typical brown, sub-rounded to round, bedded, fine to medium sized pebbles. The mudstone clasts were often deformed and squished by the other clasts (Figure 4.7). Clasts were predominantly composed of just mud and clay, but a few fine quartz grains (>1%) were found.

These clasts are likely from the underlying Ford Formation. The Ford Formation lies stratigraphically between the Jay and Morgan Formations and following the law of superposition, the clasts must come from an older lithology. The Ford Formation is the first of the basin’s lacustrine deposits. Therefore, the mudstones within the Morgan Volcanics conglomerate are most likely sourced from the Ford Formation.

5.2 Clast Count

The three clast counts were taken at different locations stratigraphically in the Morgan Volcanic conglomerate. The coordinates shown are an approximation for the locations as no GPS or cell phone reception was available.

The clast counts show the evolution of the composition of the Morgan Volcanic Conglomerate (Figure 5.4). The composition is comprised primarily of Greenland Group and basaltic clasts with minor input from quartz and mudstone clasts.

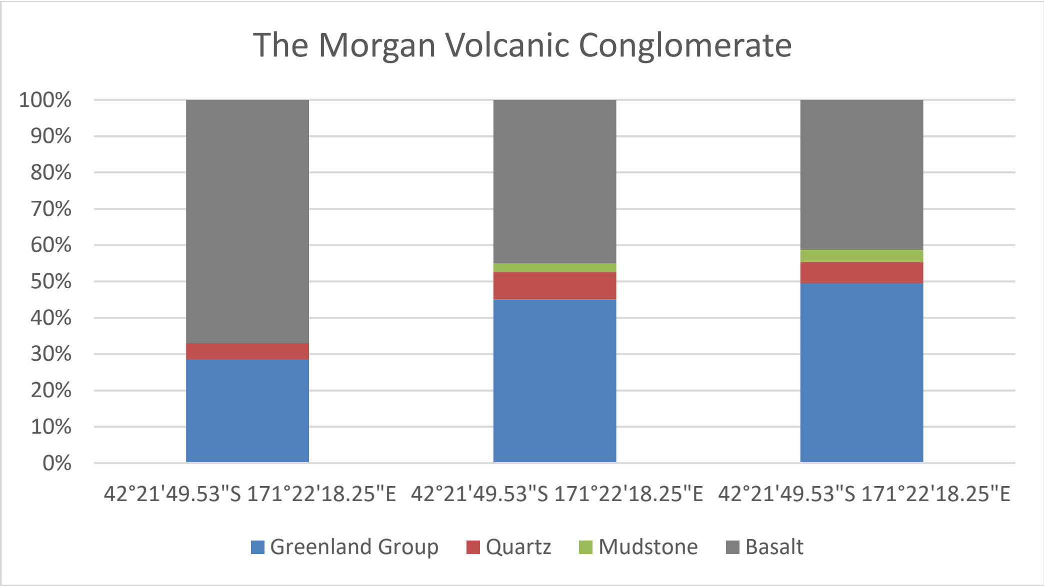

Figure 5.4 The Morgan Volcanic Conglomerate clast count results.

Initially the clast count suggests the only sediment input into the system was Greenland Group, vein quartz and the basaltic clasts. The amount of Greenland Group increases through the clast counts (Figure 5.4). This suggests that the Greenland group source was initially overwhelmed throughout the deposition. The vein quartz also increases, as it is directly related to the amount of Greenland Group exposed. The Greenland Group clasts are sourced from the basement geology and are the most predominant clast type throughout the basin's evolution.

Mudstone clasts are introduced later in the middle of the Morgan Volcanic conglomerate development, and the concentrations of these clasts increases up section (Figure 5.4). This is most likely a result of the Ford Formations influence on the basin. The Ford Formation lies stratigraphically between the Jay and Morgan Formations, and is the first of the basins lacustrine deposits (Gage, 1952; Nathan, 1985; Newman, 1985; Newman & Newman, 1992; Ward, 1997; Cody, 2015). Therefore, the mudstones within the Morgan Volcanic conglomerate are most likely sourced from the Ford Formation.

The presence of these Ford mudstone clasts, suggests that the original depression that these volcanic conglomerates formed in was uplifted, and now exposed to the rest of the basins influences (Gage, 1952; Laird, 1968; Nathan 1985; Newman, 1985).

5.3 Geochemical Analysis

Samples of the basalts were sent to Spectra Chem for geochemical analysis, to determine the major and trace elements of the clasts. The results had a rather large loss on ignitions (LOI), most likely due to the abundance of amygdaloids. Therefore, the data has been normalised for the LOI. The samples were sent to Spectra Chem for geochemical analysis before the thin sections had been returned. Therefore, the extent of the amygdaloids was unknown until it was too late. The results for the basalt clasts will be slightly skewed, as the whole rock totals determined by the XRF will be incorporating the minerals in the amygdaloids. There was a total of 9 basalt clast samples analysed (BB01, BB02, BB03, BB04, BB05, BB06, BB07, BB08 and BB09). Major elements analysed were; SiO_2, TiO_2, Al_2O_3, Fe_2O_3, MnO, MgO, CaO, Na_2O, K_2O and P_2O_5. Trace elements also analysed were of As, Ba, Ce, Cr, Cu, Ga, La, Nb, Ni, Pb, Rb, Sc, Sr, Th, U, V, Y, Zn and Zr.

5.3.1 Major Element Analysis

A TAS diagram was plotted to determine the type of basalt the clasts were. Normalised data was then used to try and account for the large LOI's during XRF.

The results of normalisation allowed for three more of the clasts to plot on the TAS diagram (Figure 5.5). Without the normalisation of the data for LOI, only one of the clasts plotted on the diagram (sample BB01) (Figure 5.5).

BB01 was the least altered of the basaltic clasts and the most reliable data point. However, samples BB05, BB06, BB09, although altered have plotted relatively consistently when compared to BB01. These samples have plotted in the picro-basalt and foidite area of the TAS diagram.

A picro-basalt is a variety of high-magnesium basalt that is very rich in the mineral olivine. It is dark with yellow-green olivine phenocrysts (20 to 50%) and black to dark brown pyroxene, mostly augite (Winter, 2010). The olivine-rich picrio-basalts often occur with the more common tholeiitic basalts (Winter, 2010).

A foidite is a rare coarse-grained igneous rock with a feldspathoid mineral content greater than 60% (Winter, 2010). Crystals of alkali feldspar, plagioclase, biotite, amphibole, pyroxene, and/or olivine may be present within the rock (Winter, 2010).

Comparing the thin section data to the supposed TAS rock classification, the minerology does not match. None of the picro-basalt samples were rich in olivine, in fact, olivine was not identified at all. Pyroxene however, was the dominant phenocryst present in the thin section which is also present in picro-basalts. The classified foidite samples also does not fit the mineralogical descriptions. These samples are meant to be coarse grained however, they were all fine grained and porphyritic. Nevertheless, the composition of a foidite is a closer match to what was observed in thin section.

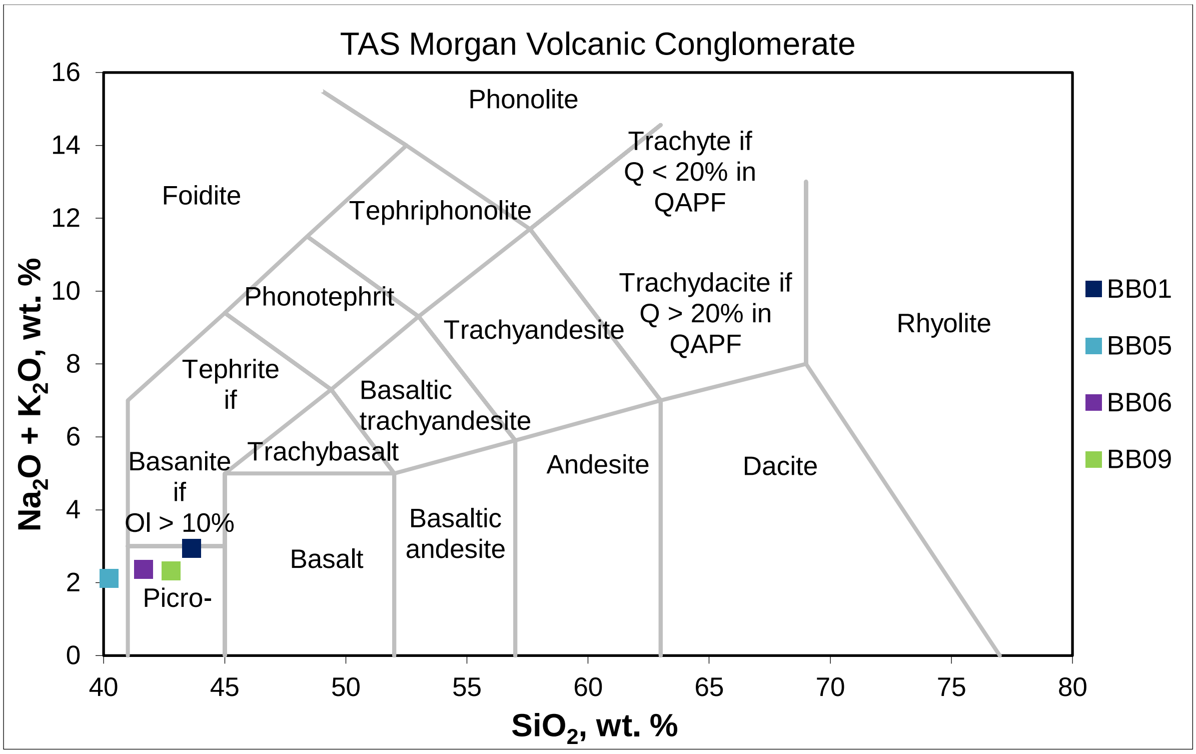

Figure 5.5 TAS Morgan Volcanic Conglomerate clasts (Le Bas et al., 1986).

These conclusions however, are all based on normalised values of clasts with considerable alteration to their original composition by diagenetic alteration and secondary mineralisation.

5.3.2 Trace Element Analysis

Trace element analysis is more reliable than major element analysis in reference to highly altered rocks (Winchester & Floyd, 1977; Middelburg et al., 1988; Winter, 2010). This is because major elements are more affected by diagenetic alteration, due to concentrations of the alteration minerals (Middelburg et al., 1988). The trace elements, especially the immobile trace elements, are more likely to be unaffected by alteration (Winchester & Floyd, 1977; Middelburg et al., 1988; Winter, 2010). The more mobile trace elements analysed are, Sr, Ba, Rb, Pb, with the more immobile elements being Zr, Hf, Fe, Al, Th, Nb, Sc and the rare earth elements (REE)(Winter, 2010). Therefore, the concentration of these elements reflect more accurately the original concentrations at the time of extrusion. The trace elements analysed were As, Ba, Ce, Cr, Cu, Ga, La, Nb, Ni, Pb, Rb, Sc, Sr, Th, U, V, Y, Zn and Zr.

A trace element rock classification plot from Winchester & Floyd (1977) was used as it uses trace elements instead of major elements, to classify the rock. It was designed to be used for highly altered rocks as it focuses on immobile elements (Figure 5.6) (Winchester & Floyd, 1977).

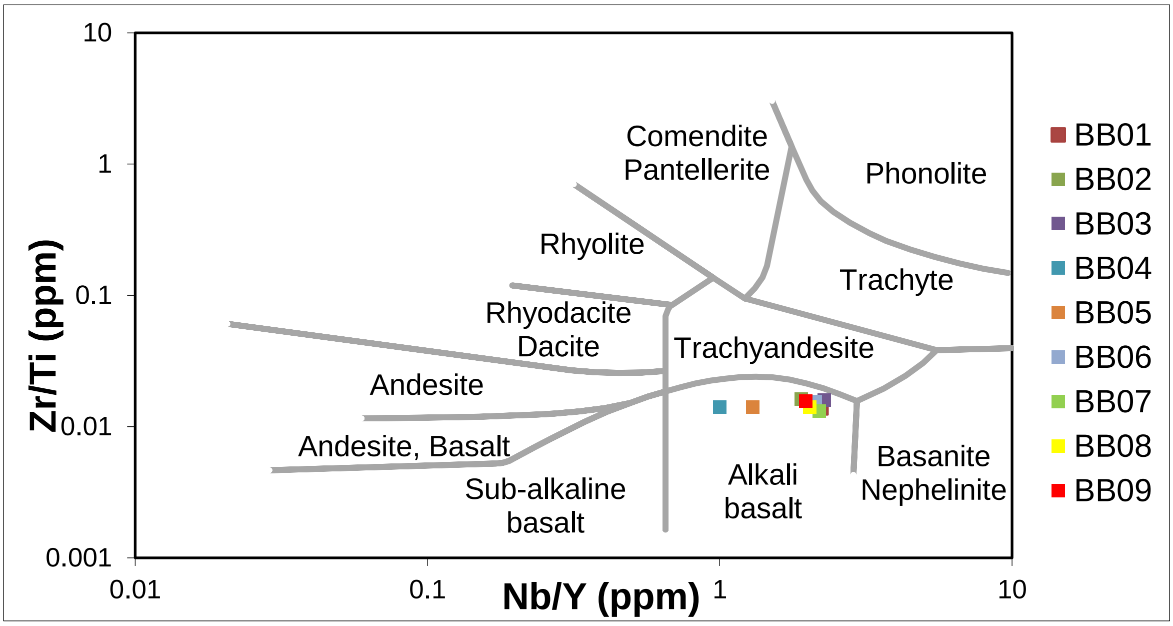

Figure 5.6 Trace element classification for the Morgan Volcanic Conglomerate basalt clasts (Winchester & Floyd, 1977).

The basalt clasts plot in the alkali basalt area on the graph (Figure 5.6). This classification of the basalt clast is more sensible than that of the picro-basalt, or foidite. The data is also a lot more reliable as the classification is based on immobile elements.

Alkali basalts are a fine-grained, dark-coloured, volcanic rock characterized by phenocrysts of olivine, titanium-rich augite, plagioclase feldspar and iron oxides (Winter, 2010). Alkali basalts are typically found on rifted continental crust (Winter, 2010).

The thin section data is similar apart from the olivine. However, this mineral is not very stable at earth's surface and therefore, could have been replaced or altered during diagenesis (Winter, 2010).

This classification of the Morgan Volcanic conglomerate basalt clasts is the most reliable and consistent with thin section descriptions. The tectonic environment in which alkali basalts form, is also consistent with current interpretations of the Greymouth Basins formation.

The Morgan Volcanic conglomerate clasts trace elements were normalised to chondrite according to Sun & McDonough 1989. This resulted in a trace element profile for the Morgan Volcanic conglomerate clasts (Figure 5.7).

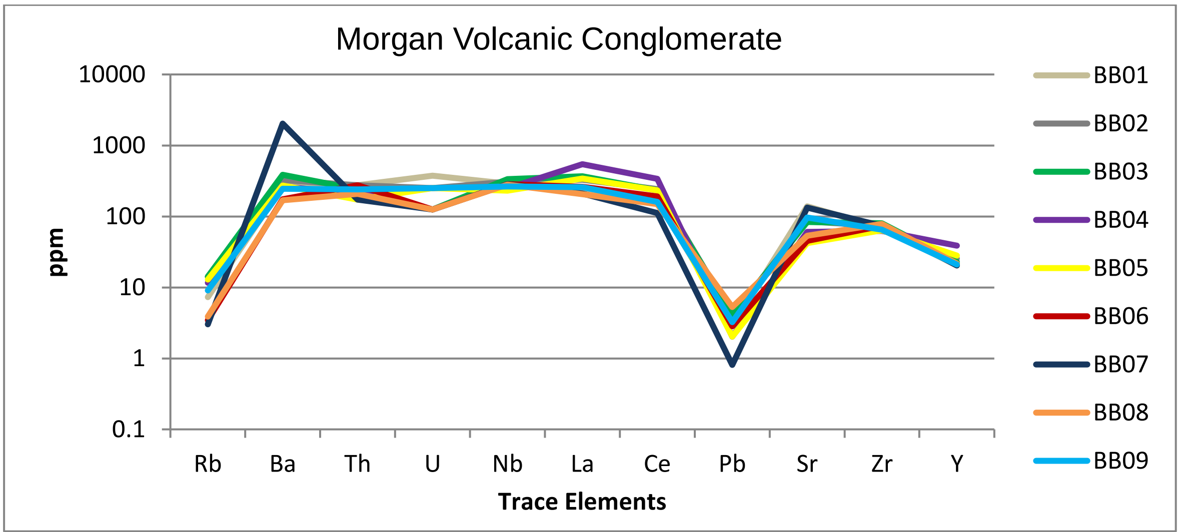

Figure 5.7 Trace Element analysis of the Morgan Volcanic Conglomerate clast results according to Sun & McDonough (1989).

The trace element profile shows that the clasts are all relatively consistent except for sample BB07, which has a considerably higher (~10x higher) concentration of barium (Ba). Barium (Ba) and strontium (Sr) are both mobile elements, which makes the high concentrations interesting (Figure 5.7) (Middelburg et al., 1988; Winter, 2010). The barium (Ba) and strontium (Sr) should be low due to weathering however, the high concentrations implies that this did not happen. This contradicts a lot of the previous data which suggests these clasts have undergone chemical alteration. However, the data could be showing the result of chemical weathering, which would suggest even higher concentrations of barium (Ba) and strontium (Sr). The higher concentration of barium could also be a result of a mineral in the amygdaloids. Zeolite minerals are difficult to distinguish and can alternate the chemistry of their composition (Deer et al., 1992).

The very low concentrations of lead (Pb) are most likely a result of weathering, as lead is considered a mobile element (Figure 5.7) (Middelburg et al., 1988; Winter, 2010).

Generally, the data is consistent except for one minor outlier (BB07). The trace element data shows minor weathering and relatively high concentrations of the trace elements, except for lead.

5.4 Comparison of basalt clasts in Rewanui Formation conglomerates to Morgan Volcanic Conglomerate clasts

Basaltic clasts also have been identified in the Rewanui Formation at 12 Mile Beach. These clasts are thought to come from some volcanism on the western side of the basin. The basaltic clasts were found throughout the Rewanui conglomerates, with a few samples of hornfels being mistaken for basalts. The hornfels clasts were identified by thin section analysis and high silica contents.

The basaltic clasts from the Rewanui Formation were plotted on the TAS diagram to compare with the two volcanic sources (Figure 5.8) (Le Bas et al., 1986).

The TAS diagram shows similar concentrations of alkali metals with the main difference being the amount of silica (Figure 5.8). The Rewanui basaltic clasts are more concentrated in silica, which could be a result of the different magma source, or the altered basaltic clasts weight percent's have been distorted due to the amgydules.

A combination of both is the most likely reason for the differences in the composition. However, the Morgan Volcanic clasts data needs to be considered with a bit of scepticism. Although sample BB01 is not altered, the other samples are and the data is therefore skewed.

The trace element profiles of the Morgan Volcanic conglomerate clasts and the Rewanui basaltic clasts have been superimposed for comparison (Figure 5.9). Both trace element profiles have been normalised to chondrite according to Sun & McDonough (1989).

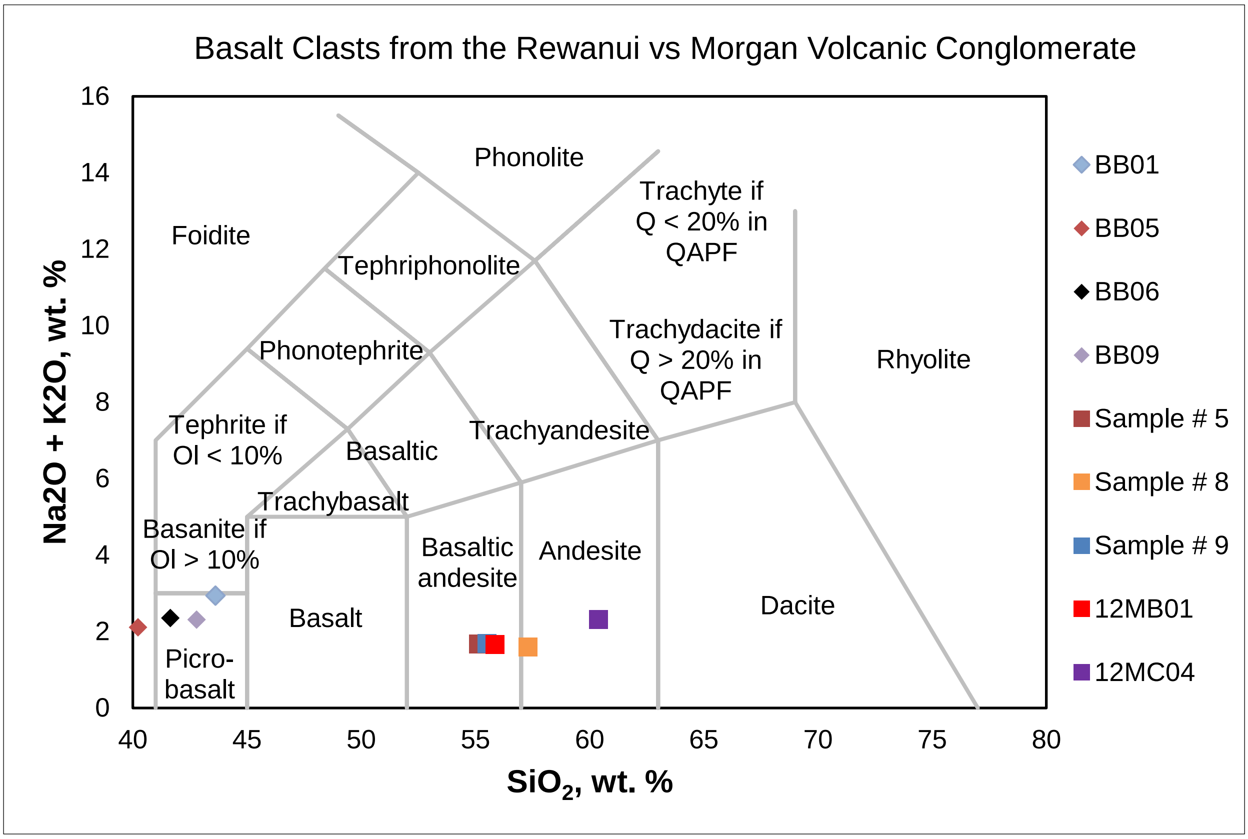

Figure 5.8 TAS of the Morgan Volcanic Conglomerate clasts compared to the basalt clasts found in the Rewanui at 12 Mile Beach (Le Bas et al., 1986).

The trace element profiles show a similar trend but generally have different concentrations for each trace element. Differences in concentration of barium (Ba), thorium (Th), niobium (Nb), lanthanum (La), lead (Pb), strontium (Sr) and zirconium (Zr). This suggests a different source and supports the previous interpretation of the major elements. The geochemical analysis result for the Rewanui basalt clasts is more reliable then the Morgan Volcanic conglomerate clasts results, due to the absence of amygdules.

This concludes that there are two different sources of volcanism associated with the rifting and basin development of the Greymouth Basin.

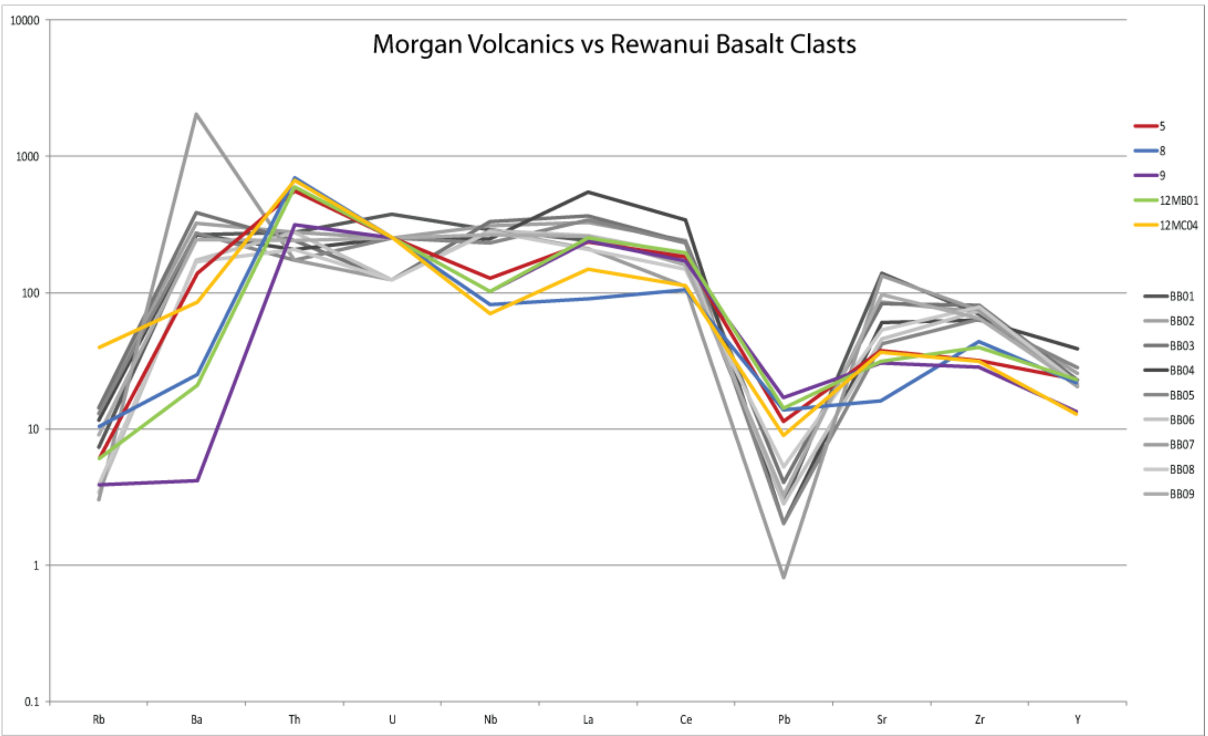

Figure 5.9 Trace Element analysis comparison of the Morgan Volcanic Conglomerate clasts and the Rewanui basalt clasts found at 12 Mile Beach results according to Sun & McDonough (1989).

5.5 Tectonic Setting

The Greymouth Basin is an extensional basin that formed in the later stages of Tasman Sea spreading (Gage, 1952; Bradshaw & Laird, 2004; Strogan et al., 2017). Lithospheric stretching is caused by either passive rifting, where localised stresses arise along plate edge forces, or active rifting, which involves upwelling of mantle melt and eruptive volcanics (Leeder, 1995). Although intrusives and volcanoclastics have been found within the Paparoa Coal Measures, these are rare, and it is determined the Paparoa sequence was formed in relation to passive rifting, associated with Tasman Sea spreading (Bradshaw & Laird, 2004).

A Tholeiitic and calc-alkaline graph was plotted with Na_2O +K_2O, FeO and MgO wt% (Figure 5.10) (Irvine & Baragar, 1971). This graph was plotted to determine the type of tectonic setting the basalt clasts are derived from (Winter, 2010). Calc-alkaline magmas are essentially restricted to subduction- related plate tectonic processes. Whereas, tholeiitic magmas are practically the exclusive magma type associated with divergent tectonic boundaries (Winter, 2010). Volcanism associated with strike slip basins is usually alkaline in composition (Tatar, Yurtmen, Temiz, Guersoy, Kocbulut, Mesci, & Guezou, 2007).

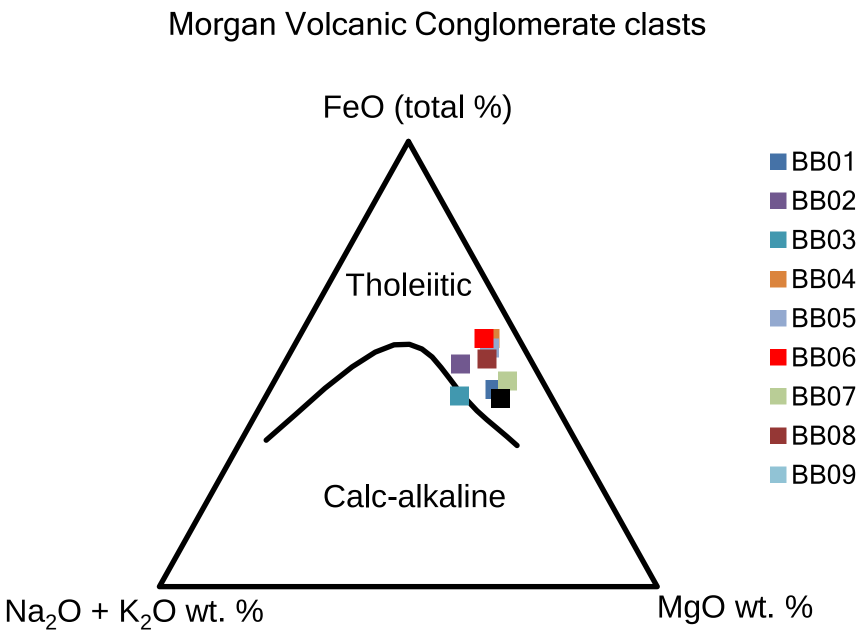

Figure 5.10 Magma composition of the Morgan Volcanic Conglomerate clasts (Irvine & Baragar, 1971).

The Irvine & Baragar (1971) tholeiitic versus calc-alkaline diagram shows that the Morgan Volcanic conglomerate clasts were derived from a tholeiitic derived magma. The data is quite consistent with very little variation between plots (Figure 5.10). This provides some reliability, as the least altered sample BB01 is clustered with the rest of the samples. Tholeiitic magma determines that these clasts were formed from a divergent tectonic boundary (Winter, 2010). This conclusion provides supporting evidence for the Greymouth Basin being formed as an extensional basin.

The same graph was used to determine the tectonic setting of the basaltic clasts found in the Rewanui Formation at 12 Mile Beach.

The Rewanui basalt clasts all plotted in the tholeiitic section of the graph except for one, sample 12MC04 (Figure 5.11). The results show that the basalt clasts found in the Rewanui Formation at 12 Mile Beach, are tholeiitic in composition. This indicates that the clasts likely formed in an extensional tectonic setting. Sample 12MC04 however, lies on the calc-alkaline portion of the ternary diagram. This is due to higher alkali metal concentrations which correlate with the clast being higher in silica and as a result, being classified as an andesite. This clast could be a hornfels clast like some of the other mistaken identity clasts. This would account for the sample 12MC04's higher concentration in silica, but mafic appearance and percent of mafic composition.

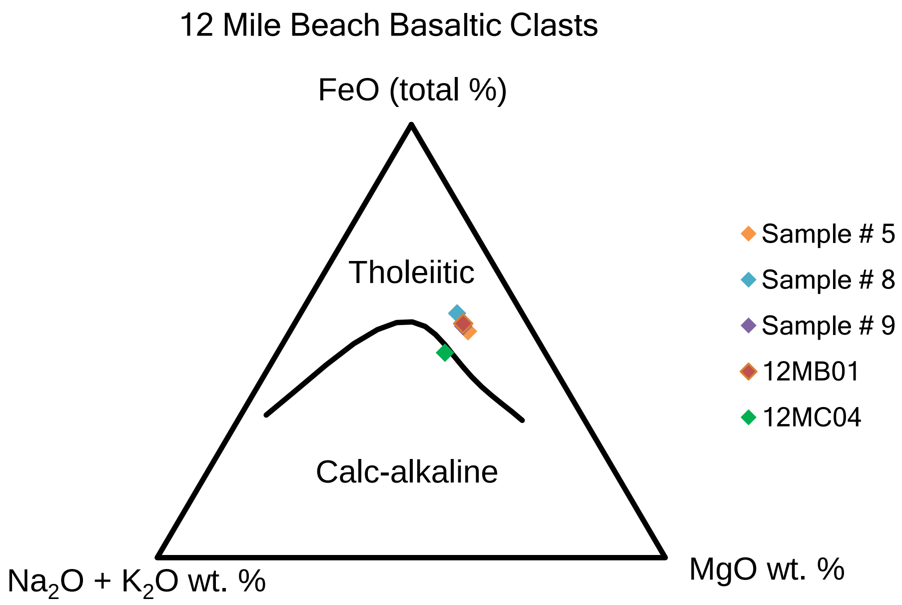

Figure 5.11 Magma composition of the12 Mile Beach, Rewanui Formation basaltic clasts (Irvine & Baragar, 1971).

Previous investigations into Greymouth Basin have led to two alternative theories on basin formation, one a pure rift setting and the other a strike slip or oblique extensional basin (Bishop, 1992; Laird, 1994; Ward, 1997). Volcanism is associated with both pure rift and oblique transtensional basins (Einsele, 1992; Leeder, 1995; Leeder, 1999; Gawthorpe & Leeder, 2000). Transtentional basins have less volcanic activity compared to pure rift basins (Einsele, 1992; Mathieu, de Vries, Pilato, & Troll, 2011). Volcanism associated with strike slip basins is usually alkaline in composition compared to the tholeiitic comprised volcanism associated with pure rift basins (Tatar et al., 2007).

Both the 12 Mile Beach, Rewanui Formation basaltic clasts and the Morgan Volcanic conglomerate clasts, indicate an extensional tectonic setting. However, this conclusion is partly derived, from some altered basaltic clasts, determined with major element concentrations, which will be skewed due to the secondary mineralisation of the amygdaloids. Therefore, the Morgan Volcanic conglomerate clast data should be considered with scepticism, even though it supports current conclusions. The basalt clasts from 12 Mile Beach, are unaltered and therefore, more reliable, which adds some confidence in the Morgan Volcanic conglomerate results.

Chapter 6 Reservoir Capability

The Greymouth basin has the capacity to become a petroleum producing basin, if all of the required criteria are met. A prospective petroleum basin needs to fulfil five criteria; have a potential hydrocarbon source, permeability/ migration, trap, cap rock and a reservoir rock (Allen & Allen, 2013; Tiab & Donaldson, 2015). The Paparoa Coal Measures have a potential hydrocarbon source with proven oil seeps originating from them (Morgan, 1911; Nathan et al., 2002; Beggs et al., 2008). The Greymouth basin is cut by numerous faults because of both its development as a failed rift system, with younger cross cutting faults from the development of the Alpine Fault, and the modern plate boundary (Nathan, 1978; Ward, 1997; Laird & Bradshaw, 2004). Faults can act as both conduits and barriers to fluid flow and therefore can be detrimental or advantageous to hydrocarbon resource. Faults also generate structural traps as long as a cap rock is present. The impermeable cap rock is crucial, as it closes and seals the hydrocarbon system (Allen & Allen, 2013; Tiab & Donaldson, 2015). The reservoir rock stores the hydrocarbons as they migrate from the source rock. A quality reservoir rock requires a good amount of porosity and permeability (Allen & Allen, 2013; Tiab & Donaldson, 2015). The porosity and the clay content will be investigated in the sandstone to determine reservoir quality.

The nature of reservoir rocks containing oil and gas, dictates the quantities of fluids trapped within the void space of these rocks, and the ability of these fluids to flow through the rocks (Allen & Allen, 2013; Tiab & Donaldson, 2015). The measure of the void space is defined as the porosity of the rock, and the measure of the ability of the rock to transfer fluids, is called the permeability. A knowledge of these two properties is essential before questions concerning types of fluids, amount of fluids, rates of fluid flow, and fluid recovery estimates can be answered (Allen & Allen, 2013; Tiab & Donaldson, 2015).

The sandstones within the Paparoa Coal Measures have been investigated to determine the potential for a reservoir rock within the Greymouth Basin. Porosity is affected by grainsize, grain shape, grainsize distribution (sorting), and the degree of consolidation and alteration (Allen & Allen, 2013; Tiab & Donaldson 2015). The sandstone samples will be examined in terms of grainsize, shape, sorting, compaction and the amount of alteration. The clay content between sand grains also affects permeability. Therefore, the degree of weathering for feldspar crystals into clay, in particular, is a concern for reservoir rocks. This study will focus on the texture of the sandstones (grainsize, shape, sorting and compaction) and the amount of clay, which has a detrimental effect on porosity and permeability (Ellison, 1958; Chilingarian, 1964, Tiab & Donaldson, 2015).

There are two main categories of porosity, primary and secondary porosity, with multiple sub categories (Ellison, 1958). This study will only be concerned with primary porosity, specifically intergranular or inter-particle pore space. Intergranular porosity is the voids between grains, the interstitial voids of all kinds, in all types of rocks (Ellison, 1958). These openings range from sub-capillary (pores less than 0.002 mm in diameter) through to super-capillary size (voids greater than 0.5 mm in diameter) (Ellison, 1958).

The porosity grainsize, shape, sorting and clay content of the samples will be determined by petrographic analysis. The void space created between grains was determined by point counting the empty void space to get a percentage of the rock that is empty. The degree of alteration to clays was also noted and considered, as it is detrimental to permeability and the overall capability and quality of the reservoir.

In many thin section studies, particularly work associated with the petroleum industry, examination of the nature and the extent of porosity in the sediment may be as important as, or more important than, the examination of mineral composition (Lewis & McConchie, 1994).

6.1 Methods

Sandstone samples were chosen with two main criteria in mind; 1. A medium grainsize where possible and 2. A suitable thickness of bed. These criteria are a few of the primary indications of a possible reservoir rock, so samples were taken accordingly (Allen & Allen, 2013; Tiab & Donaldson, 2015). However, both fine and coarse-grained sandstone exceptions were sampled due to availability.

Eleven samples were selected as the main focus of this research was on provenance. A variety of different grainsize samples were chosen, keeping the reservoir criteria in mind of a medium grained sandstone. This was because the basin had varying degrees of grainsizes throughout. Two drill holes, DH 632 in the middle of the basin and DH 660 in the north-east corner were chosen. DH 632 core location also sits close to the transition between the coarse polymictic conglomerates to the west and the finer clastic sandstone sediments to the north-east.

Each sample was described and recorded according to standard structure, texture and composition. In particular grainsize, shape, rounding and sorting were recorded. This was conducted in both hand sample and under petrographic analysis. This was because the texture of the sediment can have an effect on porosity and permeability, and will help in determining reservoir quality (Allen & Allen, 2013; Tiab & Donaldson, 2015).

A blue stain was applied to the thin section construction to accentuate the void space. The void space was highlighted by the epoxy blue stain, which aided in the quantification of void space by point counting.

The porosity point count was conducted with a simplified version of the previous sandstone point counts Gazzi-Dickinson method (Ingersoll et al., 1984). The counts only consisted of two categories, void space (blue dye) and not void space (grain). Quantitative analysis of the amounts of porosity can be made from standard point-count data, on pore space abundance (Lundegard, 1992). This determined the percent of the sample that was pore space versus grains (Dullien, 2012; Loucks et al., 2012; Houseknecht, 1987). The data acquired provided a percent of the rock sample that was pore space, which is necessary for a potential reservoir rock in a petroleum play.

6.2 Results

Four samples from drill hole 632 from the Rewanui Formation (79, 83, 89 and 92) were analysed. Sample 79 was taken from a pale green grey, moderately sorted, sub-angular to sub-rounded, 1.3m thick, lithic to quartz rich, coarse sandstone, with interbedded scattered carbonaceous material (Figure 6.1). This sample was the deepest at 465.9 m to 465.95 m down the drill hole. The point count total was 635 counts with 567 grains, versus 68 voids which is 10.7% void space and 89.3% grains. Sample 79 had varying feldspar alteration ranging from minor to extreme alteration. Examples of this range of alteration are shown in the sandstone provenance chapter. Feldspar alteration was determined to be 30% of the thin section, with 3% of clays likely to be originally deposited at time of deposition.

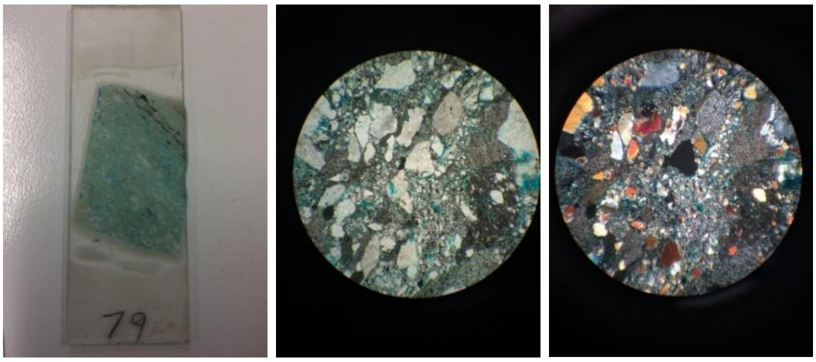

Figure 6.1 Sample 79 thin section in plain and cross polarised light, from the Rewanui Formation at 465.95m.

Sample 83 was taken from a green grey, well sorted, 7.1m thick, sub-angular to sub-rounded, quartz rich medium sandstone with scattered variable mud, clay and carbonaceous streaks at a depth of 447.1m to 447.15m (Figure 6.2). The point count total was 708 counts with 560 of grains, versus 148 void space counts, 20.9% void space and 79.1% grains. Sample 83 had varying feldspar alteration ranging from minor to extreme alteration. Feldspar alteration was determined to be 30% of the thin section, with 7% of clays likely to be originally deposited at time of deposition.

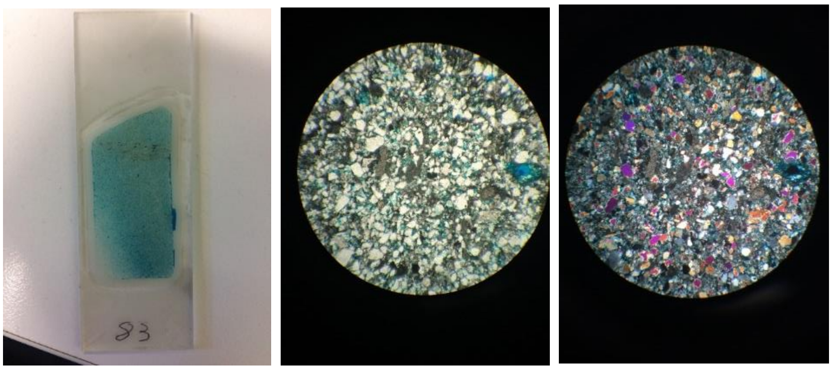

Figure 6.2 Sample 83 thin section in plain and cross polarised light, from the Rewanui Formation at 447.1m.

Sample 89 was taken from a pale grey to off white, poorly sorted, sub-angular to sub-rounded, 1.4m thick, medium sandstone (Figure 6.3). Predominantly quartz and feldspar dominated, with pale green Greenland Group and carbonaceous lithics. This sandstone bed was sampled from a depth of 369.64m to 369.69m. A total of 635 counts were undertaken producing 68 counts of void space and 567 counts of grains, which is 10.7% void space and 89.3% grains. Sample 89 had varying feldspar alteration ranging from minor to extreme alteration. Feldspar alteration was determined to be 30% of the thin section with 10% of clays likely to be originally deposited at time of deposition.

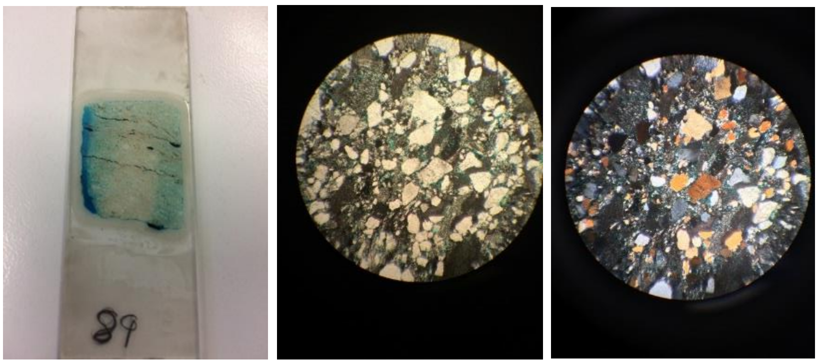

Figure 6.3 Sample 89 thin section in plain and cross polarised light, from the Rewanui Formation at 369.64m.

Sample 92 was taken from an off white, well sorted, sub-angular to sub-rounded, thin bed of only 20cm thick coarse sandstone (Figure 6.4). Comprising of quartz, with only minor feldspar and carbonaceous material lenses, this sample was taken from a depth of 348.2m to 348.25m. A total of 629 point counts were conducted, with 189 void space counts and 440 grain counts, which are 30.1% void space and 69.9% grains. Sample 92 had varying feldspar alteration ranging from minor to extreme alteration. The thin section contained 10% of altered feldspar, with 1% of clays likely to be originally deposited at time of deposition.

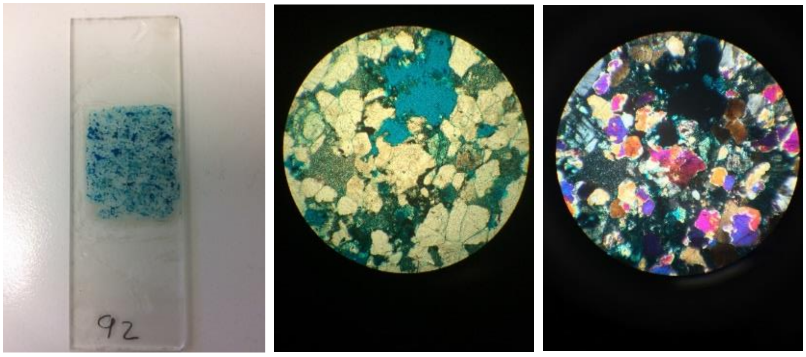

Figure 6.4 Sample 92 Thin section in plain and cross polarised light, from the Rewanui Formation at 348.2m.

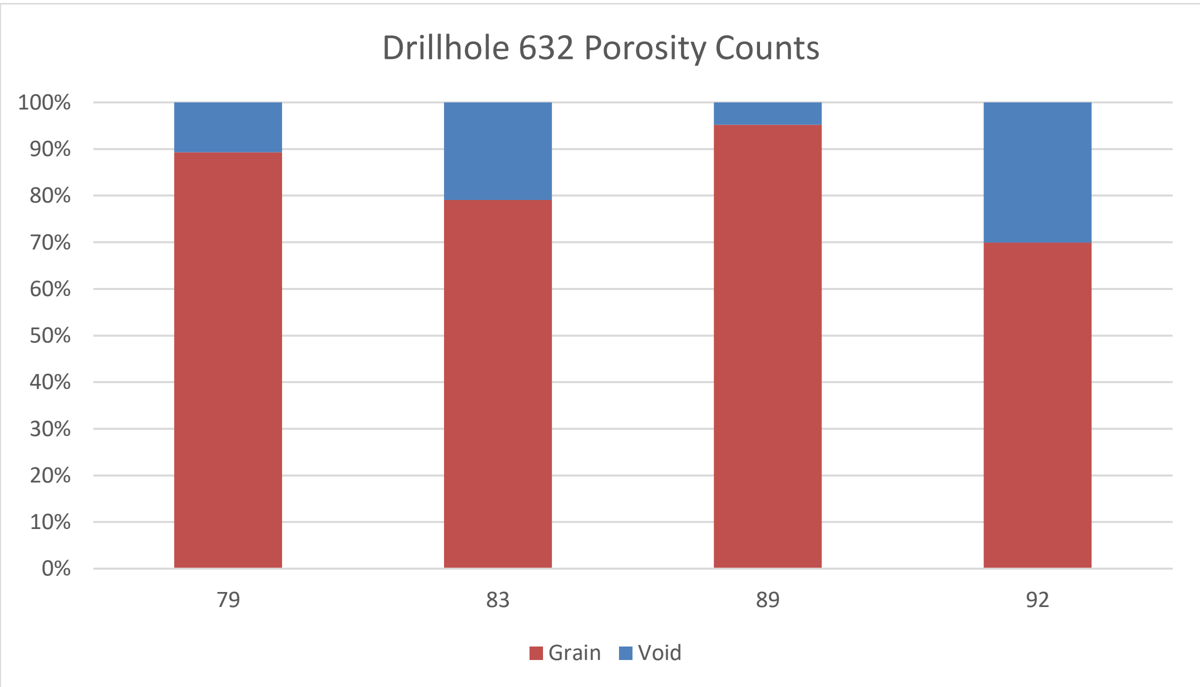

Figure 6.5 DH 632 porosity results.

Drillhole 660 had seven samples (27, 63, 62, 61, 46, 44, and 32) analysed. Sample 27 was collected from the Morgan Formation with the others from the Rewanui Formation. Sample 27 was taken from a green to brown, moderately to well sorted, sub-angular to sub-rounded, 1.5m thick, medium sandstone (Figure 6.6). This sample was quartzose with lithics and some mudstone grains, taken from a depth of 253.3m to 253.6m. The point count total was 649 counts with 637 grains versus 12 void space which is 1.8% void space, and 98.2% grains. Sample 27 had varying feldspar alteration, ranging from minor to extreme alteration. This sample was very fine grained, which made it difficult to determine weathered feldspars from original clay deposition. The thin section contained 5% of altered feldspar, with 30% of clays likely to be originally deposited at time of deposition.

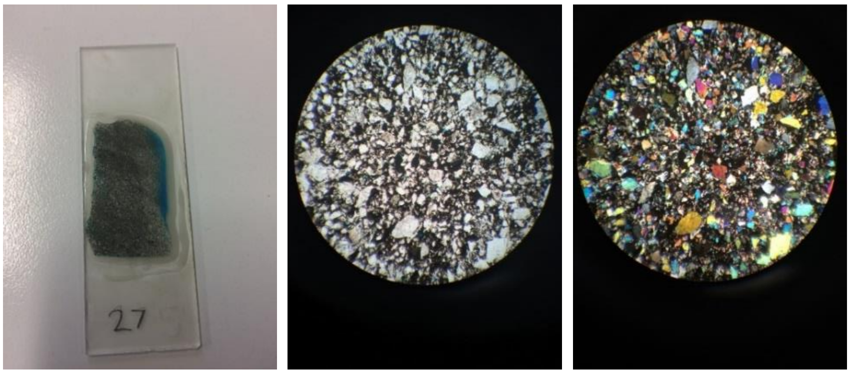

Figure 6.6 Sample 27 Thin section in plain and cross polarised light, from the Morgan Formation at 253.3m.

Sample 63 was taken from pale brown to off white, well sorted, sub-angular, 0.6m thick coarse sandstone (Figure 6.7). Comprised of quartz and feldspar, with 20% reworked mudstone grains and 10% lithics taken from a depth of 183.6m to183.65m. The point count total was 754 counts with 475 of grains versus 279 void space counts, which is 37% void space and 63% grain. Sample 63 had varying feldspar alteration, ranging from minor to extreme alteration. The thin section contained 5% of altered feldspar, with 2% of clays likely to be originally deposited at time of deposition.

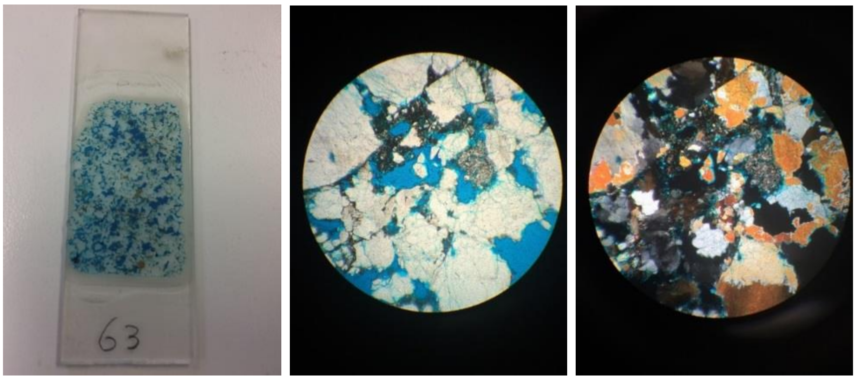

Figure 6.7 Sample 63 thin section in plain and cross polarised light, from the Rewanui Formation at 183.6m.

Sample 62 was taken from a pale cream, well sorted, sub-angular to sub-rounded, 1.2m, thick coarse sandstone bed, at a depth of 181.6m to 181.65m. This sample was quartzose, with minor feldspar, mud and other lithics (Figure 6.8). A total of 673 counts were undertaken, producing 208 counts of void space and 465 counts of grains, which is 31% void space and 69% grains. Sample 62 had varying feldspar alteration, ranging from minor to extreme alteration. The thin section contained 7% of altered feldspar, with 15% of clays likely to be originally deposited at time of deposition.

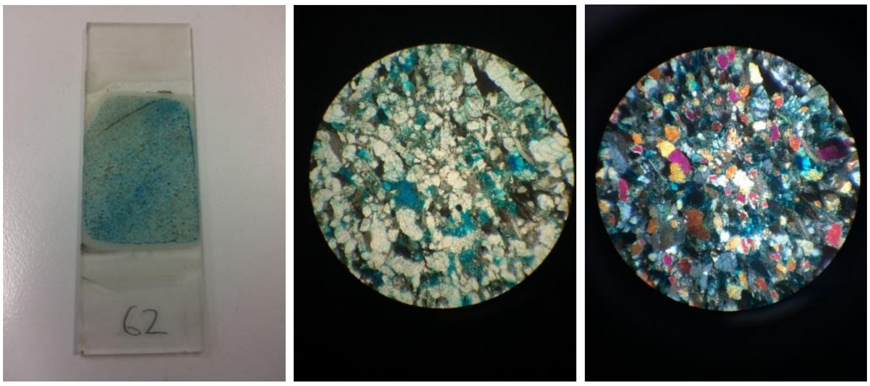

Figure 6.8 Sample 62 thin section in plain and cross polarised light, from the Rewanui Formation at 181.6m.

Sample 61 was taken from a pale brown to cream, moderately sorted, sub-angular to sub-rounded, very thin bed of only 0.6m thick, coarse sandstone (Figure 6.9). This sample was quartzose with feldspar and minor lithics, and was collected from down the drill hole at a depth of 178.8m to 178.85m. A total of 637 point counts were conducted, with 213 void space counts and 424 grain counts, which are 33.4% void space and 66.6% grains. Sample 61 had varying feldspar alteration, ranging from minor to extreme alteration. The thin section contained 24% of altered feldspar, with 7% of clays likely to be originally deposited at time of deposition.

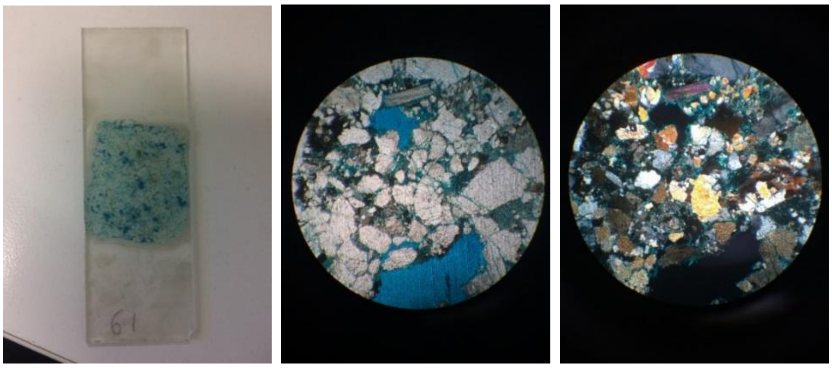

Figure 6.9 Sample 61 thin section in plain and cross polarised light, from the Rewanui Formation at 178.8m.

Sample 46 was taken from a pale brown, well sorted, sub-angular to sub-rounded, bed of only 0.9m thick fine sandstone (Figure 6.10). The sample was quartzose and micaceous, with minor carbonaceous streaks from a depth of 130.3m to 130.35m. A total of 596 point counts were conducted, with 7 void space counts and 589 grain counts, which are 1.2% void space and 98.8% grains. Sample 46 had varying feldspar alteration, ranging from minor to extreme alteration. This sample was very fine grained, which made it difficult to determine weathered feldspars from original clay deposition. The thin section contained 15% of altered feldspar, with 10% of clays likely to be originally deposited at time of deposition.

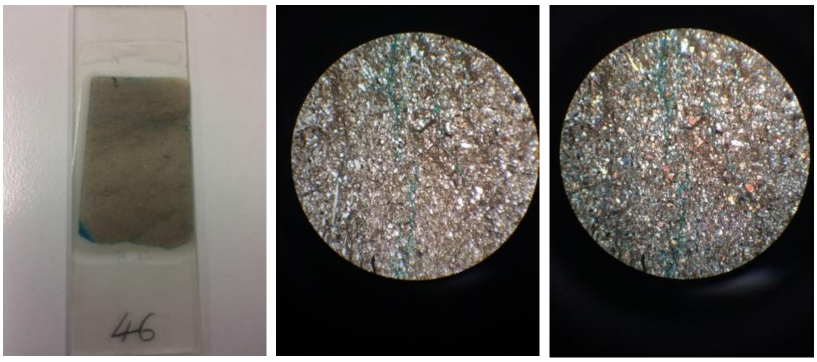

Figure 6.10 Sample 46 thin section in plain and cross polarised light, from the Rewanui Formation at 130.3m.

Sample 44 was taken from a pale cream to off white, well sorted, sub-angular to sub-rounded, bed of 6.1m thick coarse sandstone (Figure 6.11). The sample was quartzose with feldspar, micas and lithics, coming from a depth of 124.6m to 124.65m. A total of 699 point counts were conducted with 253 void space counts and 446 grain counts, which are 36.2% void space and 63.8% grains. Sample 44 had varying feldspar alteration, ranging from minor to medium alteration. The thin section contained 8% of altered feldspar, with 2% of clays likely to be originally deposited at time of deposition.

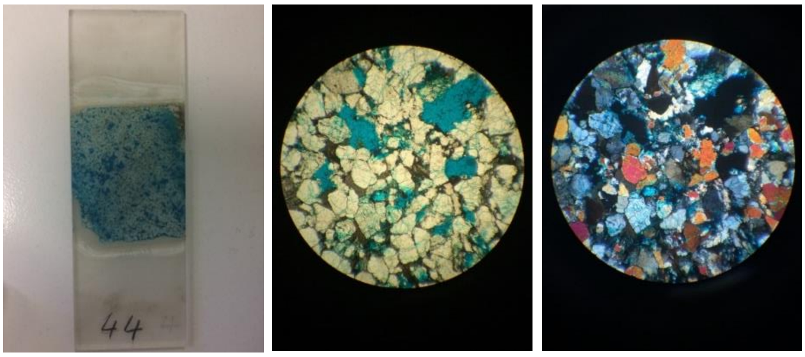

Figure 6.11 Sample 44 thin section in plain and cross polarised light, from the Rewanui Formation at 124.6m.

Sample 32 was taken from a pale cream brown, moderately sorted, sub-angular to sub-rounded, 0.6m thick medium sandstone (Figure 6.12). This sample was quartzose and micaceous, with mudstone and minor feldspars, taken from a depth of 89.1m to 89.15m. A total of 633 point counts were conducted, with 108 void space counts and 525 grain counts, which are 17% void space and 83% grains. Sample 32 had varying feldspar alteration, ranging from minor to extreme alteration. The thin section contained 15% of altered feldspar, with 25% of clays likely to be originally deposited at time of deposition.

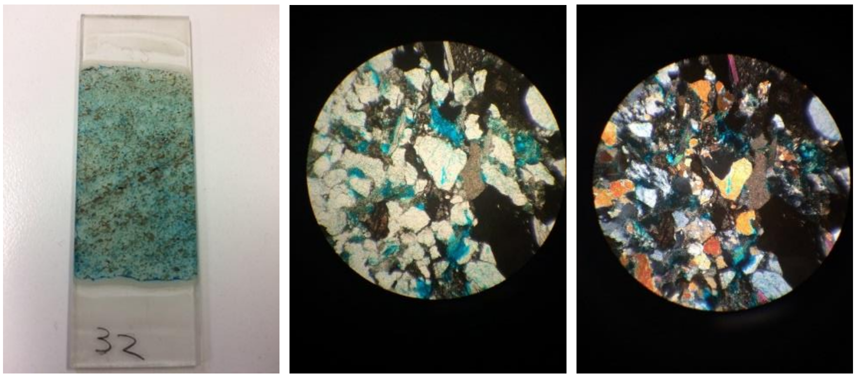

Figure 6.12 Sample 32 thin section in plain and cross polarised light, from the Rewanui Formation at 89.1m.

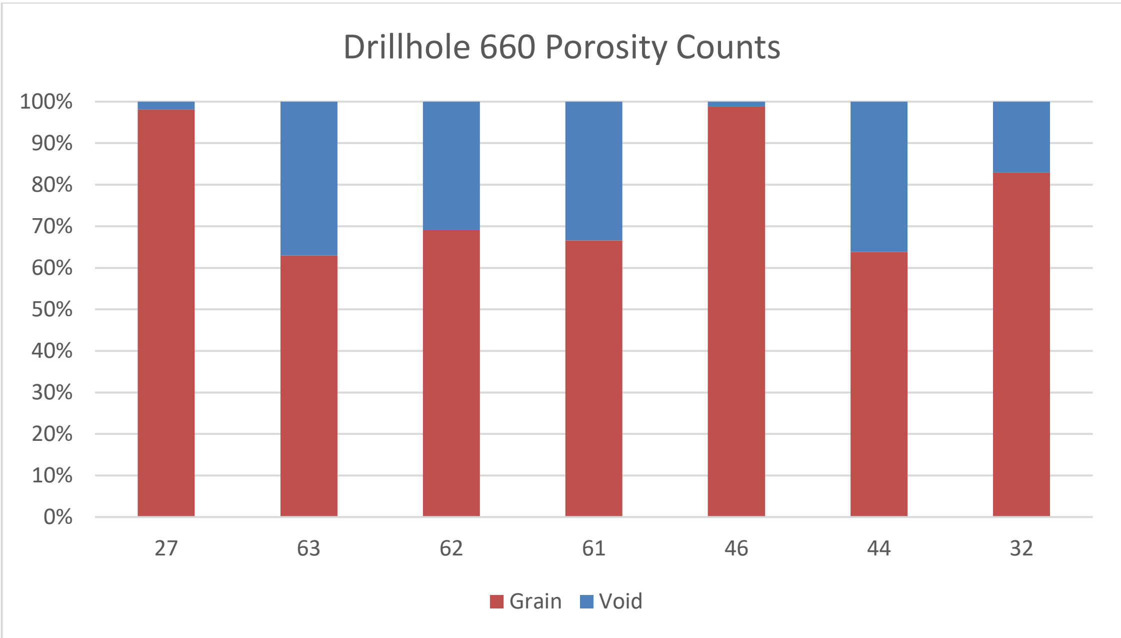

Figure 6.13 DH 660 porosity results.

6.3 Analysis and Interpretation

The results show a variety of porosities across the samples. The high porosities in drill hole 660 are indicative of a quality reservoir rock (Figure 6.13). The samples were analysed in terms of grainsize, shape, sorting, location, formation, and compaction against porosity. The amount of clay was also investigated as it has a detrimental effect on porosity and permeability. These characteristics can affect the porosity of the sandstones, reducing the quality of any reservoir potential.

6.3.1 Burial Depth and Location

Burial Depth

The degree of compaction during and after deposition decreases interstitial void space, especially the finer-grained sedimentary rocks (Allen & Allen, 2013; Tiab & Donaldson, 2015). Compaction is generally negligible in closely packed sandstones or conglomerates, but porosity is lower in deeper, older rocks (Allen & Allen, 2013; Tiab & Donaldson, 2015). Therefore, the depth of the sample is crucial as the depth and compaction are directly related. The deeper the sample is taken from, the more pressure and overbearing weight the lithology is subjected to. The compaction reduces the intergranular space between grains, and subsequently reduces the overall porosity (Ellison, 1958; Chilingarian, 1964, Tiab & Donaldson, 2015).

The sandstone porosity samples are compared to the depth they are sampled from (Figure 6.14). The trend shows a decrease in the porosity, the deeper the samples came from.

Drill hole 632 samples all come from the Rewanui Formation, commencing at the deepest with sample 79, coming from a depth of 465.9m to 465.95m. The drill hole 632 results have a general trend of increasing porosity up the drill hole. This can be attributed directly to the amount of compaction and diagenesis the samples received due to depth (Ellison, 1958; Chilingarian 1964; Boyd & Lewis, 1995; Tiab & Donaldson, 2015). The correlation is illustrated in the drill hole 632 samples shown in figure 6.14.

Sample 27 in drill hole 660 sample set is from the Morgan Formation, and deepest at a depth of 253.3m to 253.6m. It has one of the worst porosities in the sample set. The drill hole 660 sample set has a relatively flat trend for porosity versus depth and compaction. This could be attributed to the samples being at relatively shallow depth, where compaction has not yet affected these samples significantly. Again, direct compaction of the grains has not been measures, but considered in analysis interpretation.

Drill hole 632 sample set shows a direct relationship between depth/compaction and porosity, whereas the drill hole 660 sample set seems to show no trend. This could be attributed to the depth of which the samples were taken, as drill hole 660's sample set was much shallower than drill hole 632's and therefore, had not been subjected to the same compaction.

The porosity of the sandstones in the Paparoa Coal Measures reduces with an increase in burial.

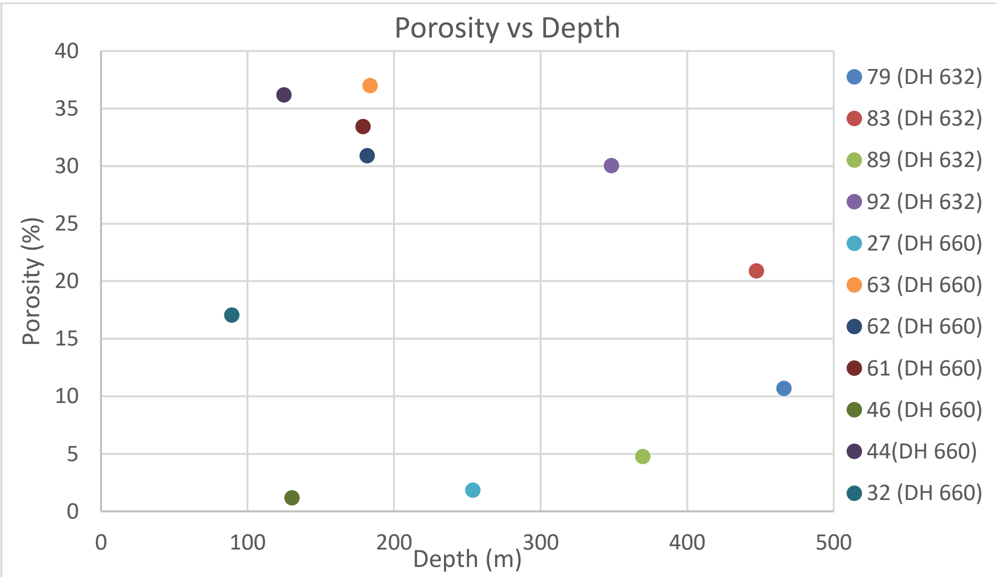

Figure 6.14 Graph showing porosity of samples vs depth sampled from core.

Location

Two drill hole locations were the source of the porosity data, with drill hole 632 located in the centre of the basin, and drill hole 660 in the north east on the eastern side of the basin. With the two different locations representing two portions of the basin, the data can be presented with respect to the centre compared to the north-east.

Drill hole 632 sample represents the centre of the basin axis and the transition between the two different clastic sediment lithologies, cobble to boulder, polymictic conglomerates to the north-west and the finer, fine to coarse sand sediments to the south-east. The centre of the basin is interbedded with multiple lacustrine deposits (Figure 3.5) (Waiomo and Goldlight Formations) (Gage, 1952, Nathan, 1978, Newman, 1985, Newman & Newman, 1998 and Cody, 2015). Due to this location the amount of mud and clay introduced to the sandstones would be increased. Muds and clay are detrimental to porosity, as these smaller fragments can fill the space between the grains more efficiently (Allen & Allen, 2013; Tiab & Donaldson, 2015). This is evident in the drill hole 632 samples as they have more mud, clays and carbonaceous material present. This is represented in some of the samples porosity results for drill hole 632, as there are a few samples with low porosities.

Drill hole 660 represents the north-eastern side of the basin axis which is dominated by finer sandstones (Gage, 1952, Nathan, 1978, Newman, 1985, Newman & Newman, 1998). The samples had generally less mud and clay and as a result, the porosity for this location is higher, with the exception of two samples that did have high mud and clay content (Figure 6.13).

The results show that the north-eastern side (DH 660) of the basin axis was overall more porous than the centre (DH 632) of the basin axis.

6.3.2 Sandstone textures and Facies

The texture of the sandstone is an important characteristic when determining the quality of a reservoir rock. Grainsize, sorting, and shape are a result of the depositional facies. The depositional facies can influence all characteristics of a lithologies texture.

Sorting

Sorting is the gradation of grains. If small particles of silt or clay are mixed with larger sand grains, the effective (intercommunicating) porosity will be considerably reduced. Sorting depends on at least four major factors: size range of material, type of deposition, current characteristics, and the duration of the sedimentary process (Fraser & Graton, 1935; Allen & Allen, 2013; Tiab & Donaldson, 2015).

The sorting for the porosity samples ranged from poorly sorted to well-sorted. The only poorly sorted sample (sample 89 from drill hole 632) had the third lowest porosity with 4.8 %, of the data set. Whereas, the moderately sorted samples (samples 79, 27, 61 and 32) had a large variation of porosity in terms of sorting. These samples ranged from 1.8% to 33% porosity. The well sorted samples (sample 44, 46, 62, 63, 83 and 92) porosity also had a large variation, ranging from 1.17% to

37% porous. Results show that the moderate to well sorted samples tend to have higher porosities.

Grainsize and Shape

The porosity data set varied from fine to coarse grained sandstones. The fine sandstone sample 46, had the lowest porosity of all the samples. The medium grained sandstone samples (83, 89, 27 and 32) had varying degrees of porosity. The coarse sandstone samples (44, 92, 79 63, 62 and 61) all had significantly high porosities apart from sample 79 with 10.7% pore space. The results in reference to grainsize was variable. The fine sandstone sample 46 confirms the theory of lower porosities for finer grained sediments (Ellison, 1958; Chilingarian, 1964, Tiab & Donaldson, 2015). However, the medium sandstones sediments were incredibly variable, with a large range of 1.17% to 20% porous. The coarser sandstones samples were generally the most porous with the exception of sample 79.

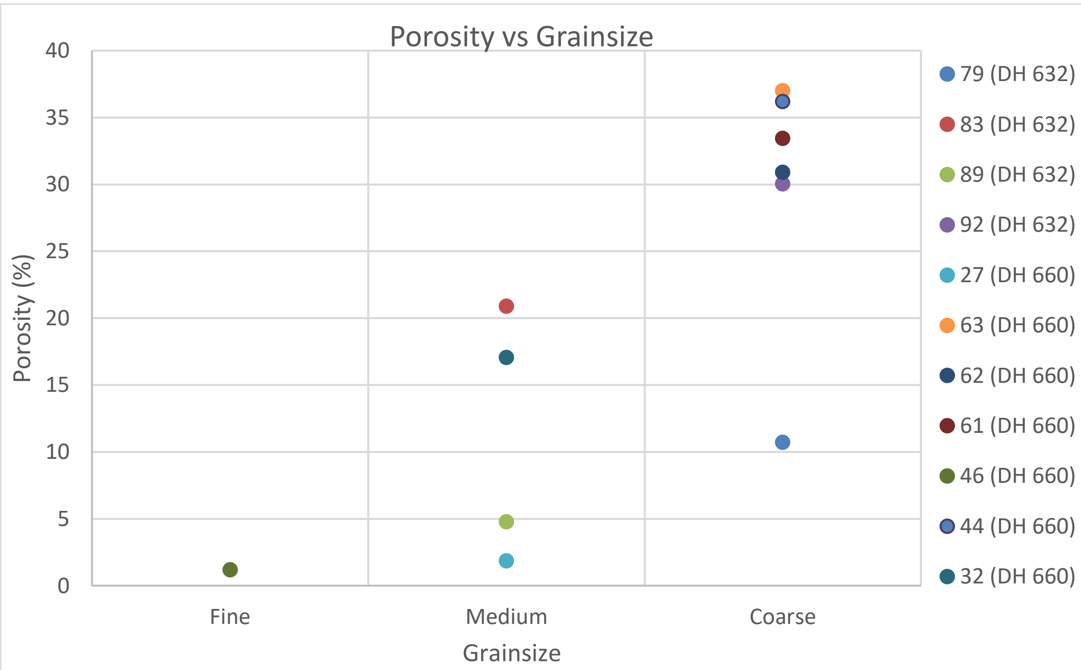

Figure 6.15 Graph showing porosity vs grainsize.

The angularity or shape of the grains is another governing factor for porosity, as more rounded particles leave larger voids in-between them. All but one of the porosity samples were sub-angular to sub-rounded. Sample 63 was sub-angular but had a rather high porosity. The other samples were determined to be sub-angular to sub-rounded, and all had varying degrees of porosity including the lower porosity samples. These results indicate that alone the angularity and size of the grains does not determine the porosity of the samples within the Paparoa Coal Measures.

Facies

The centre of the basin (DH632) is dominated primarily by a meandering river/delta and lacustrine depositional facies (Gage, 195; Nathan, 1978; Newman, 1985; Ward, 1997). The centre of the basin therefore, has a higher mud and clay component which is evident in the sandstone samples (Table 6.1) However, this facies varies spatially, as it can produce well sorted channel sandstones and clay rich flood plains sandstones facies (Johnsson & Basu, 1993; Leeder, 1999; Reineck & Singh, 2012). Therefore, depending on the part of the facies intercepted by the drill hole, the porosity will change. The well sorted channel sandstones would produce higher porosities, than samples of the clay rich flood plain sandstones (Gage, 195; Nathan, 1978; Newman, 1985; Ward, 1997). This could be attributed to drill hole 660's higher porosities, as it too was located in a meandering river/delta and lacustrine depositional environment (Gage, 195; Nathan, 1978; Newman, 1985; Ward, 1997). The 660 drill hole most likely intercepted the more fluvial channelized sandstones within the meandering river and delta facies, as the samples were sorted and coarser grained (Gage, 195; Nathan, 1978; Newman, 1985; Ward, 1997).

The sandstone depositional facies and the location within the Paparoa Coal Measures, will affect the texture and therefore the porosity of the sandstones.

6.3.3 Alteration

The alteration to clay or cementing material between sand grains also affects permeability, especially where fresh water is present. Some clay, particularly smectites (bentonites) and montmorillonites, swell in fresh water and have a tendency to partially or completely block the pore spaces (Allen & Allen, 2013; Tiab & Donaldson, 2015). Therefore, the degree of weathering for feldspar crystals into clay in particular is a concern for reservoir rocks. The chemical alteration of feldspar to sericite, illite and clays, can reduce the ability for migration of hydrocarbons from pore to pore.

Clay material is detrimental to porosity and permeability (Ellison, 1958; Chilingarian, 1964, Tiab & Donaldson, 2015). There was feldspar alteration to clays in every sample to varying degrees (Boyd & Lewis, 1995). Illite has been shown to form in the early stages of burial (Boyd & Lewis, 1995). The samples varied from minor to extremely altered, with a range of 5% to 30% feldspar alteration. These values are only the percent of alteration thought to be caused by diagenesis. Previously deposited clay material was approximated with some samples having higher original clay content than the alteration clays.

Drill Hole	Sample #	Feldspar Alteration %	Original Clays %	Porosity %
632 (Centre of Basin)	79	30	3	10.7
	83	30	7	20.9
	89	30	10	4.7
	92	10	1	30
660 (North-east of Basin)	27	5	30	1.8
	63	5	2	37
	62	7	15	30
	61	24	7	33
	46	15	10	1.17
	44	8	2	36
	32	15	25	17

Table 6.1 Showing porosity samples, feldspar alteration and original clay percentages against porosity values.

The figure and results show that although feldspar alteration does influence the porosity, it appears the amount of clay at deposition has a more significant influence. However, there are also samples (32 and 62) that have a relatively high porosity, even with significant original clay content. It appears that the sample results for high porosities generally came from the samples with the least feldspar alteration, and original clay content. The results show that the amount of clay, especially the amount of originally deposited clay content in the Paparoa Coal measures sandstones, reduces the porosity.

6.4 Permeability

The amount of original and altered feldspar clay material in the samples was generally substantial. Both alteration and deposited original clay material was quantified. Clay material in a prospective reservoir rock, whether it is caused by diagenesis or original material, is detrimental to the rocks ability to allow fluid flow (Ellison, 1958; Chilingarian, 1964; Boyd & Lewis, 1995; Tiab & Donaldson, 2015). There are a few samples that had low alteration and original clay content with high porosities. These samples (44, 61, 62, 63 and 92) were the most promising in terms of prospective reservoir rocks. The lack of clay and high porosity implies relatively high permeability.

The results above in terms of governing factors for porosity are individually, moderately influential. Therefore, a medium to coarse grained, quartzose, well sorted, low clay influence, relatively shallow sandstone from the Paparoa Coal Measures, are potential reservoir rocks. The results also show that the sandstones primarily in the north-east have a greater porosity and permeability.

6.5 Discussion

The porosity and permeability results from this study are important to the petroleum industry, for future investigations into the Greymouth Basin as a potential hydrocarbon source. The results will provide a greater understanding with regards to the prospective potential of the Paparoa Coal Measures, as a reservoir for hydrocarbon storage. The Paparoa Coal Measures are a recorded source of hydrocarbon generation in the area, and now with this additional information relating to reservoir capability, the Greymouth Basin displays greater potential as a petroleum play.

The porosity results show that there is reservoir capable sandstones within the Paparoa Coal Measures. The results were analyses in terms of the texture of the sandstones (grainsize, shape, sorting and compaction), as well as the amount of clay which has a detrimental effect on porosity and permeability. The results demonstrate that all of the textures analysed, influenced the porosity of the sandstones to some degree. The grainsize, depth and clay content, primarily originally deposited clay content, were the most influential affecting the porosity and permeability of the sandstones within the Paparoa Coal Measures.

The texture of the sandstone samples are a consequence of the depositional facies responsible for the deposition of the sediment facies (Johnsson & Basu, 1993; Leeder, 1999; Reineck & Singh, 2012). Grainsize and original clay content are controlled by the depositional environment. The smaller localised depositional environments, within the overall facies, play an important role in determining porosity with the Paparoa Coal Measures. Therefore, the distribution of facies can be used to determine reservoir rocks throughout the basin.

The porosity results show some considerably high porosityies within a number of the samples (up to 37% porous). This porosity could be a misrepresentation of the original sediment, due to probable plucked grains during thin section construction. There is a possibility that the void space counted was the result of a lost grain. However, this would only account for some of the determined porosity, as the majority of the samples had reasonable porosity values.

With the presence of quality reservoir rock present within the Paparoa Coal Measure, the lack of cap rock and traps in the Greymouth Basin become a problem for the prospective petroleum play. However, there are lithologies within the basin that could potentially act as a cap rock and seal. The Goldlight Formation is a thick lacustrine formation, which could act as a potential seal for the system. There are however, multiple problems for this lithology to act as the seal for the system. The Goldlight Formation is not spatially consistent across the entire basin (Gage, 1952; Nathan, 1978; Newman, 1985; Cody, 2015). This formation interfingers the coarser polymictic conglomerates to the west, and the finer grained clastic sandstones to the east. Therefore, it would not be a viable seal or cap rock, unless structurally deformed to make a trap. Even with structural deformation, the likelihood of this lithology acting as a potential seal is low.

The Greymouth basin is structurally deformed with multiple generations of faults running through it (Gage, 1952: Nathan, 1978: Newman, 1985). Therefore, there is a possibility of an unknown structural trap within the basin, however unlikely.

The porosity and permeability results suggest that the Greymouth Basin does contain some good reservoir rock. (Allen & Allen, 2013; Tiab & Donaldson, 2015). The Greymouth Basin has had documented cases of petroleum generation and the aim of this study was to determine the viability of a reservoir rock within the basin. The Greymouth basin can now meet three of the five criteria required for a petroleum play. The lack of cap rock and trap however, reduces the prospectively of the basin. Nevertheless, these results, do confirm that there are porous rocks, with likely high permeability within the Paparoa Coal Measures and Greymouth Basin. Subsequently, making this study a good introductory investigation for the petroleum industry into the Paparoa Coal Measures.

Chapter 7 Conclusions and Comparison to Taranaki

The aim of this research was to address the provenance of the sandstones and conglomerates of the Paparoa Coal Measures, as well as their porosity in relation to a possible petroleum reservoir. This addressed the variations in interpretation surrounding the compositions of the clastic sediments of a western granitic source (Gage, 1952) vs. an eastern granitic source (Newman, 1985, Newman 1987, Newman & Newman, 1992) as well as provided a better understanding of the non-coal bearing units and their relevance to the West Coast-Taranaki Rift System. The provenance investigation was also used to help interpret the basin geometry, which can provide more information regarding the petroleum prospects in the region, and can be applied to future petroleum exploration in New Zealand, especially in the Taranaki Basin.

7.1 East versus West Controversy

The controversy between Gage (1952) and Newman (1985) outlined at the beginning of this study showed two suggested provenance interpretations of the Paparoa Coal Measures. Gage (1952) believed that there was a granitic source to the north-west and a Greenland Group source to the south-east (Gage, 1952).

Newman (1985) suggested that the Rewanui sediments had a granitic source, but it was located to the east of the basin with the well exposed conglomeratic facies in the north-west largely Greenland Group derived. Newman (1985) believed that the quartzose sandstones on the eastern side of the basin were dominated by granitic source detritus deposited by fluvial systems along the main axis of the faulting. Newman (1985) states, that she believed that Gage (1952) was incorrect.

The results show that the Paparoa Coal Measures in the Greymouth Basin was fed by two principal sediment sources (Gage, 1952; Nathan, 1978; Newman, 1985; Newman & Newman, 1992; Ward, 1997). The north-western basin margin supplied sand and gravel derived from Paleozoic Greenland Group basement, and an A-type granite inferred offshore. Whereas, the north-eastern axial sandy fluvial system carried the dominant granitic derived detritus and Greenland Group influence into the basin. The polycrystalline quartz and muscovite sediment entered the basin via the same north eastern axial drainage system, and suggests a high grade metamorphic source, most likely the Charleston Metamorphic Group to the north. The results show that both Gage (1952) and Newman (1985) were correct to a degree, as there are granitic sources in both directions, although possibly different granites.

The granitic component on the north-western side of the basin has been determined to be neither the Karamea nor the Rahu Suite, but an alkali granite that was present to the north-west during the Late Cretaceous. The geochemistry of the clasts determined that they did not fit either of the Karamea or Rahu Suite granites, but was typical of an A-type granite (Andrew Tulloch, pers. comm. 2017). There is evidence of granites offshore of the West Coast, with the closest well intercepting granite at basement being the Kongahu-1 well, offshore of Karamea (Wiltshire, 1984). This well intercepted a deformed Cretaceous granite as basement rock (Wiltshire, 1984). Therefore, granites are found offshore (Tulloch et al., 1992; Andrew Tulloch, pers. comm. 2017). Clast geochemistry indicates there is likely an A-type granite offshore of the Greymouth Basin.

7.2 Model for Greymouth Basin

The Greymouth Basin conforms to the typical asymmetrical half graben rift basin outlined by Leeder & Gawthorpe (1987). The sedimentary facies interpretation has shown that the basin consisted of steep topography in the north-west likely caused by uplift on the footwall of the main bounding normal fault (Bassett, Cody, Monteith, & Maitra, 2014; Cody, 2015; Maitra & Bassett, 2016; Maitra, Bassett, Nicol, & Sykes, 2016; Maitra & Bassett, 2017b; Maitra & Bassett, 2017c). The up thrown highlands shed higher energy braided rivers and gravelly deltas (12 Mile Beach and DH634). The Highlands are eroded away as the Eocene Brunner sediments lie unconformably on Greenland Group basement, offshore at the Haku-1 well (Hematite Petroleum, 1970). The low gradual slope towards the centre of the basin in the north-east (DH 660) and south-west (DH 649), indicate two axial drainage rivers and the entrance of external sediment into the basin (Maitra & Bassett, 2016; Maitra et al., 2016; Maitra & Bassett, 2017b; Maitra & Bassett, 2017c). The presence of low energy facies in the centre of the basin (DH 632), suggests that there is a topographic low at this location. The south-eastern side of the basin (DH 620) is dominated by low to moderate energy level facies, indicating a gradual slope. The gradual sloping topography towards the basins centre from the south-east (DH 620), indicates the hinge lowlands of the half graben were in this direction (Bassett et al., 2014; Maitra & Bassett, 2016; Maitra & Bassett, 2017b; Maitra & Bassett, 2017c). This indicates the fourth source area for the finer clastic sediments, lies to the south-east.

The conglomerates indicate where high energy steep topography was located at different times in the basin’s history, and therefore, the location of extensional faults can be determined (e.g. Gawthorpe & Leeder, 2000). The older conglomerates (Jay and Morgan Formations) are located in small patches throughout the basin suggesting there were numerous localised extensional faults and depocentres (Maitra & Bassett, 2017). Thus the initiation of extension in the basin was distributed across the area in small sub-basins. The younger conglomerates (Rewanui and Dunollie Formations) are located only on the north-western side of the basin, illustrating that at those times extension and subsidence were dominated and controlled by the north-western boundary fault. This illustrates a change from small localized faults to a larger asymmetrical rift half graben basin, with continued extension (e.g. Gawthorpe & Leeder, 2000).

The size of the clasts (up to large boulders) in the conglomerates in the north-west at 12 Mile Beach and DH 634, indicate that the source was relatively close. The presence of the older conglomerates of the Morgan Formation and the Waiomo lake, suggests that the 12 Mile Beach section is not directly up against the fault scarp of the dominant extensional fault (Figure 3.1, 3.2 and 3.3). Sediments lying directly against the foot wall would be young in ag,e and lie unconformably on basement relative to the other Paparoa Coal Measures. Therefore, the presence of the older conglomeratic Morgan Formation and lacustrine dominated Waiomo Formation at 12 Mile Beach, suggest the boundary fault for the Greymouth basin is off shore, to the north-west of 12 Mile Beach. The Haku-1 well located offshore to the west of the Greymouth Basin shows that Eocene Brunner sediments lie directly on Greenland Group basement (Hematite Petroleum, 1970). This unconformity indicates the primary boundary fault for the Greymouth Basin is located somewhere between the Haku-1 well and 12 Mile Beach. The Cape Foulwind fault is located offshore and could be the boundary fault for the Greymouth Basin.

The three dominant clast types (Greenland Group, granite and hornfels), suggest that the sediment catchment in the up thrown highlands on the north-west side, was extensive. The evolution of this catchment illustrates the unroofing of the granitic pluton source, with the introduction of first aplite and hornfels, followed by the introduction of the granite clasts. Aplite is the fine crystalline version of pegmatites, which are formed from residual eutectic granitic liquids intruded into the country rock (Winter, 2010). Aplite represents the final crystallization products of magma during the latest stage of pluton emplacement and melt crystallization (Winter, 2010). The hornfels clasts are formed by contact metamorphism, and is likely the result of the contact metamorphism areole around the intruded granitic body into the Greenland Group. The alkali granite intruded into the Greenland Group during the extensional regime and is likely the source of the aplite and cause of the hornfels. Alkali granites are commonly associated with continental rifting (Winter, 2010) and therefore, a likely source for the granitic clasts in the north-west.

The centre of the basin is dominated by finer facies of meandering rivers alternating with lacustrine (Maitra and Bassett, 2016; Maitra & Bassett, 2017b; Maitra & Bassett, 2017c). This is typical of a half graben tectonic setting, where sediment supply is unable to keep up with subsidence to completely fill the accommodation created by extension (Leeder and Gawthorpe, 1987). The lacustrine facies illustrates periods of increased subsidence, and an increase in accommodation with inadequate sediment supply (Einsele, 1992; Leeder, 1995; Leeder, 1999; Gawthorpe & Leeder, 2000). The meandering river facies indicate slightly decreased subsidence, with the centre of the basin dominated by axial rivers and drainage coming from the north-east and the south-west (Maitra & Bassett, 2016; Maitra & Bassett, 2017b; Maitra & Bassett, 2017c). This is evident with the alternation of lacustrine and meandering river facies along the south-west to north-east cross section (Figure 3.4). This axial drainage transports sediment from outside the basin, into the basin centre.

The south-eastern side of the basin is represented by drill hole 620. This location also records alternating lacustrine and meandering river/delta facies, indicating it is closer to the basin axis than the hinge of an asymmetrical half graben rift basin (Figure 3.4). This suggests that the true hinge of the basin is either further east, but missing from the Greymouth Basin or that there is another major fault bounding the south-eastern side, forming a full graben. The missing hinge of the Greymouth basin was cut by the Mount Davy fault. Cody (2015) concluded that there was a deep lake right up against the Mount Davy fault, with no sediment input. Suggate (2015) concluded that this fault was not yet active at the time, as the bed thicknesses do not change. Therefore, with the fault near the centre of the basin, and inactive until after the formation of the Paparoa Coal Measures, it is reasonable to conclude that a portion of the hinge of the basin is missing.

Point count data from the centre of the basin also support an interpretation of axial river flow. The quartz composition of older sandstones indicates local sediment sources of a low rank metamorphic source, and a plutonic source. These have been identified as Greenland Group, a local sediment source, and an undetermined plutonic source, Karamea Suite, Rahu Suite or the inferred A-type granite source. The sandstone compositions support an open basin with an axial drainage fluvial setting, during the time of the Rewanui Formation. Axial drainage runs parallel to the boundary fault and hinge axis in the final stages of basin development (Leeder, 1999; Gawthorpe & Leeder, 2000). Drill holes 649, 632 and 660 show multiple types of quartz. The Karamea Suite is one of the major granitic intrusions on the West Coast. The Karamea Suite's closest granitic body is the Barrytown granite, located just to the north of the Greymouth Basin. The Rahu Suites closest occurrence is north (Buckland Granite), next to the Charleston Metamorphic Group. The alkali granite is inferred to the north-west of the basin. The granitic derived detritus entered the basin by axial drainage rivers, and due to this, any and all of these granitic bodies are a potential source. The Rahu Suite is the most probable source with proven detrital influence from the Charleston Metamorphic Group and the Buckland granite next to it (Figure 4.16).

Strained polycrystalline and polycrystalline quartz, and a muscovite component, indicate a higher grade metamorphic source than the Greenland Group. The polycrystalline quartz and muscovite likely entered the basin predominantly from the north-east, as it is more abundant in DH 660 (NE) than in DH 649 (SW). The Charleston Metamorphic Group is also to the north of the basin, making it the likely source for the higher grade metamorphic mineral presence.

Point count analysis of the sandstones determined the tectonic setting of the Greymouth Basin to be a continental rift basin. The point count data was plotted on a quartz, feldspar, lithics (QFL) diagram to determine the tectonic setting (Dickinson & Suczek, 1979; Dickinson, Beard, Brakenridge, Erjavec, Ferguson, Inman, Knepp, Lindberg, & Ryberg, 1983). The QFL diagram determined a transitional continental tectonic setting, most likely a rift (Dickinson & Suczek, 1979; Dickinson et al., 1983).

The geochemical analysis of the basalt clasts found in the Rewanui Formation and the Morgan Volcanics conglomerate suggest, that they formed in a rift basin. Basalt clasts found in the Rewanui Formation and the Morgan Volcanics conglomerate were derived from tholeiitic magma, which is consistent with asymmetrical rift basins which produce high amounts of volcanism and are tholeiitic (Tatar et al., 2007; Mathieu et al., 2011). The basalt clasts found in the Rewanui Formation and the Morgan Volcanics are different in composition, indicating that there were two sources of volcanism within the Greymouth Basin, with the Morgan Volcanics localised to one corner of the basin. Therefore, all the basaltic clast analyses suggest an extensional tectonic setting.

The tectonic model for the Greymouth Basin is of an extensional rift that matured through time, as the sub-basins merged and widened (Figure 7.1). Basaltic volcanism indicates a tholeiitic magmatic source consistent with asymmetric rifts. Conglomerates indicate the location of fault scarps, and their propagation and linkage through time. During the final stages of the basin, thick conglomerates to the north-west show where the dominant boundary fault was located. The depocentres in the middle of the basin alternated between lacustrine and meandering fluvial rivers, with floodplains and coal mires scattered around the low gradient landscape. During times of increased sedimentation or decreased accommodation, the centre of the basin was dominated by axial river drainage, predominantly from the north-east with some entering the basin from the south-west. The hinge was dominated by meandering rivers and deltas forming down a low gradient slope towards the centre of the basin, with coal and floodplains forming alongside.

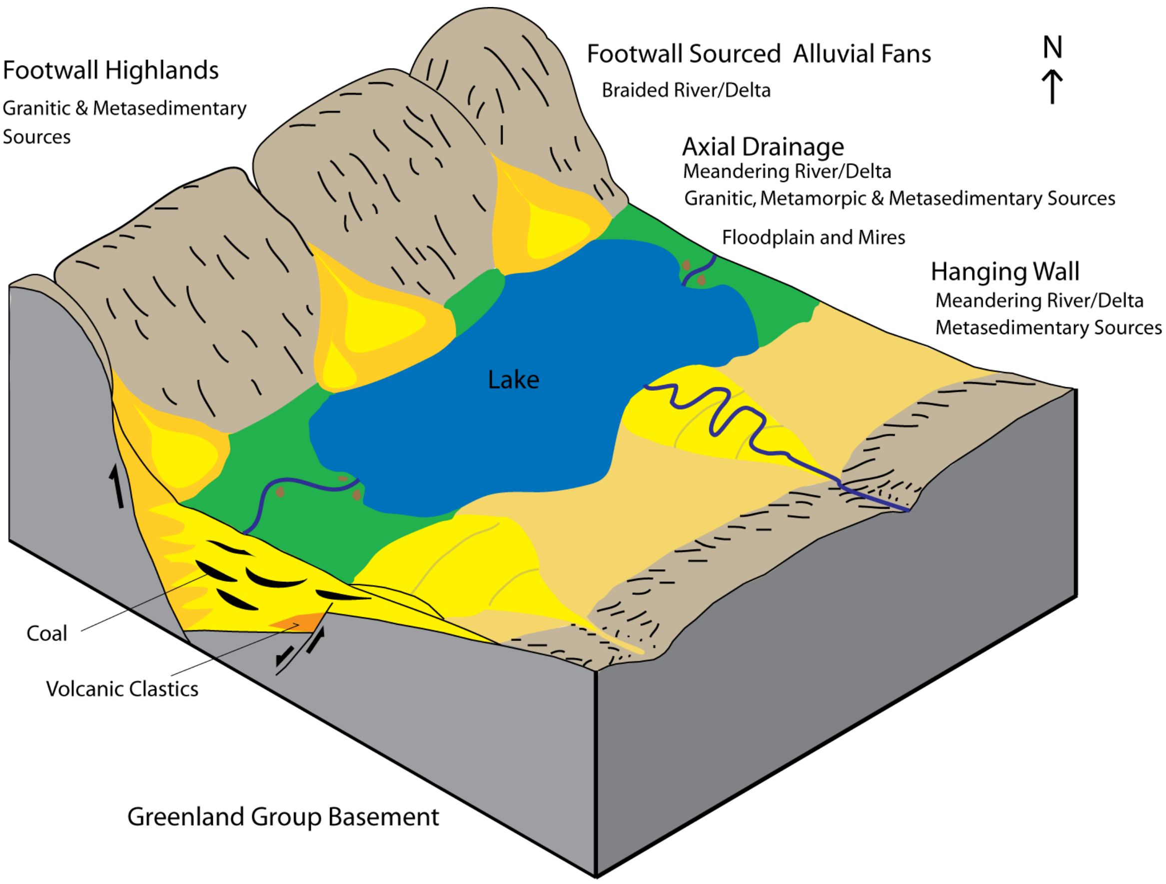

Figure 7.1 Illustration of the Greymouth Basin and Sources.

A modern analogue for the Greymouth Basin is the Lake Edward rift lake in the East African Rift (Figure 7.2). Lake Edward is a half graben rift basin, with a complete terrestrial sequence of braided rivers and deltas along the boundary fault on the west side of the basin, meandering rivers/deltas running along the axis as axial drainage and the lacustrine sediments interfingering the other facies (Figure 7.2) (Ebinger & Scholz, 2012). This Lake Edward rift lake is a perfect modern example of the geometry the Greymouth Basin has been concluded to be.

Figure 7.2 Lake Edward rift lake in the East African Rift (Image edited from www.google.com/earth/).

7.3 Offshore Greymouth

There is a history of petroleum shows in the Greymouth Basin. The Paparoa Coal Measures are a proven source rock for hydrocarbons (Morgan, 1911; Nathan et al., 2002; Beggs et al., 2008; Zink & Sykes, 2010). With a viable hydrocarbon source rock, the next step in determining a viable petroleum play is to determine a reservoir rock. A quality reservoir rock requires two characteristics; porosity and minimal clay content. The sandstone within the Paparoa Coal Measures were investigated with respect to these two reservoir rock characteristics.

The porosity and clay content results suggest that the Greymouth Basin does contain some good reservoir rock, within the meandering river/delta deposits. These high porosities and low clay content are constrained to the well sorted, coarser grained channelized fluvial sediments within the meandering river/delta deposits.

The Greymouth Basin can now fit three of the five criteria required for a petroleum play. The lack of cap rock and trap however reduces the prospectively of the basin.

These problems may be less of an issue in the basins both offshore and to the south of Greymouth. The half graben Takutai Basin shows undifferentiated Paparoa Group strata are present in the offshore petroleum exploration (Figure 7.3) (Bishop, 1992; Suggate, 2014). The subsurface continuity of the Paparoa Coal Measures in the lower Grey Valley area is unknown, and younger (Oligocene) strata are known to overlie basement in some drill holes (Matthews, 1990).

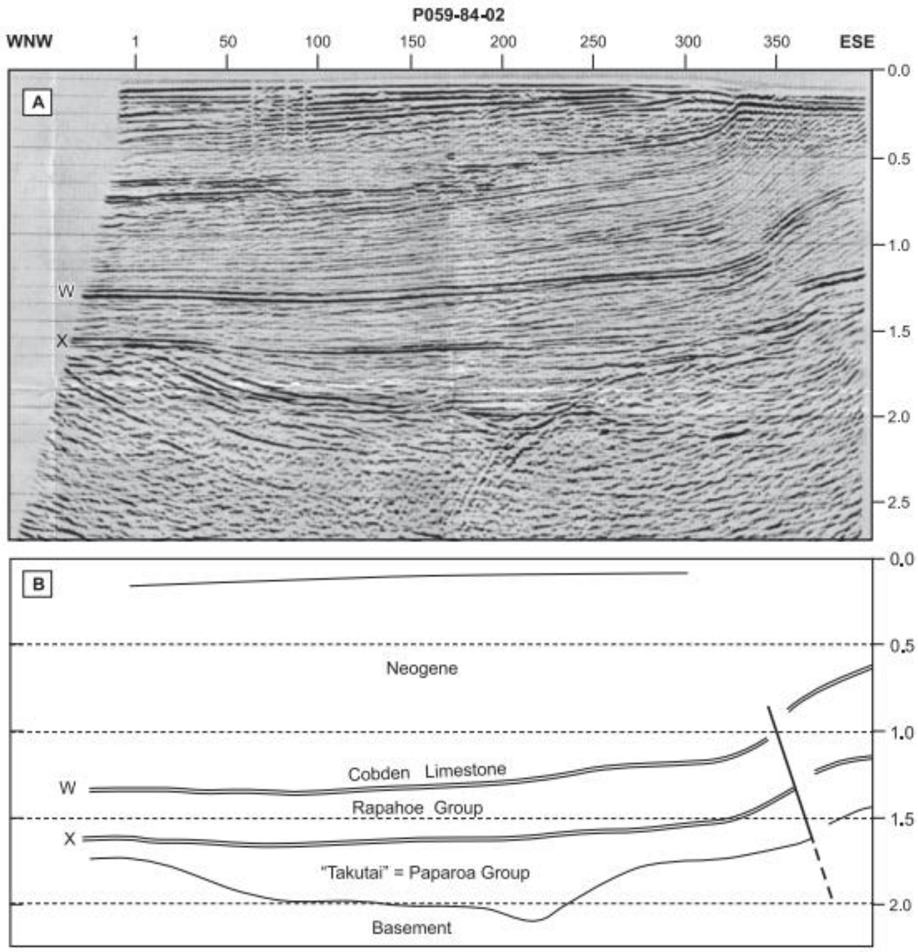

Figure 7.3 Seismic line P059-84-02of the Takutai Basin showing a graben interpreted to contain the Paparoa Coal Measures (Suggate, 2013).

The Paparoa Coal Measures are present in seismic profiles from the south-western end of the offshore Takutai half-graben (Bishop, 1992; Suggate, 2014). In particular, the transparent reflectors indicate probable lacustrine facies with very strong reflectors indicating coal present (Barrier, Nicol, & Browne, 2017). The use of facies interpretation to infer the basin geometry of the Greymouth Basin can be applied to the coeval Takutai Basin. Thus, we can infer that the Takutai basin contains coal bearing deposits and meandering river/deltas, which are likely to be as of high-quality hydrocarbon source and reservoir rocks, as in the meandering river/deltas in the Greymouth Basin.

The Takutai Basin is of interest as it provides the remaining two characteristics required for a producing petroleum play, a structural trap (half graben) and a cap rock (the Rapahoe Group) (Figure 7.3). The overlying Rapahoe Group contains an extensively thick sequence of marine mudstone known as the Kaiata Mudstone (Nathan et al., 2002). This lithology would be ideal for a cap rock (Allen & Allen, 2013; Tiab & Donaldson, 2015). The half graben structure also identified in the Takutai basin would fulfil the last of the criteria needed for a prospective petroleum play.

This hints at a potential petroleum play in the Takutai Basin which may have been overlooked, and requires further investigation to determine the economic viability.

7.4 Wider Ramifications

The Taranaki Basin is New Zealand's only hydrocarbon producing basin and has been extensively studied for several decades (Strogan et al., 2017; Uruski, 2008; Higgs, King, Raine, Sykes, Browne, Crouch, & Baur, 2012; Sykes, Volk, George, Ahmed, Higgs, Johansen, & Snowdon, 2014 and References therin). The Taranaki Basin was formed during the break up of Gondwana and the initiation of the Tasman Sea spreading (Strogan et al., 2017). During this extension, the Greymouth and Taranaki Basins were formed at the same time, as part of the same rift system (Strogan et al., 2017). The initiation of the Tasman Sea spreading, allowed for the formation of localised grabens and half grabens all along the rift. Although the primary source rocks within the Taranaki Basin are Eocene in age (Petroleum Basin

Explorer, Sykes et al., 2014), Late Cretaceous sediments have been recognised as productive (Higgs, Arnot, Brown, & Kennedy, 2010). Late Cretaceous source and reservoir rocks were deposited in the form of coal and coaly source rocks, along with potential lacustrine mudstones, deltas and sandstones (Petroleum Basin Explorer; Higgs, Zwingmann, Reyes, & Funnell, 2007; Higgs et al., 2010).
The Taranaki Basin is very similar to the Greymouth Basin in many ways, with regards to the tectonic setting formation and depositional environments within the basin (Petroleum Basin Explorer; Higgs et al., 2007; Higgs et al., 2010). However, due to the depth to Late Cretaceous sediments in the Taranaki Basin, there is a lack of drill hole data, which has resulted in main interpretations being made using seismic data accompanied with limited outcrop onshore and well data (Petroleum Basin Explorer; Higgs et al., 2010). The interpretation of seismic data alone, makes the location of prospective petroleum plays difficult. In comparison, the Greymouth Basin is intercepted by over 1000 drill holes, as well as having greater outcrop availability despite dense bush and steep topography.

Understanding the distribution of sediments in the more accessible Greymouth Basin can be applied to the Taranaki, and other rift basins within New Zealand, to provide more information on facies distribution, which leads to a higher chance of determining petroleum plays within a basin. The Paparoa Coal Measures sandstone constituent was investigated in this study with respect to reservoir rock characteristics. Results determined that there was considerable porosity and permeability culminating in some potentially high-quality reservoir rocks within the Late Cretaceous sediments. In terms of source rock, the Paparoa Coal Measures are proven to be a hydrocarbon producing source (Morgan, 1911; Nathan et al., 2002; Beggs et al., 2008; Zink & Sykes, 2010).

The Greymouth Basin sedimentological and provenance analysis, has shown that there are large variations in lithology and grainsize of the clastic sediments within the basin. The facies distribution will provide information on the possible locations of reservoir rocks within the Cretaceous aged sediments. The sandstones near the centre of the basin (DH 632), had a higher concentration of clay and mud material with lower porosities. This was likely due the lacustrine influences at this location. The channelized sandstones within the meandering rivers in the north-east (DH 660) were generally better sorted, having the best porosity due to sorting and grainsize. Therefore, the geometry of the facies present will influence the potential of the reservoir quality.

Given the similarities in basin formation, potential source rock and reservoir characteristics of Taranaki and Greymouth, the Paparoa Coal Measures should be considered as another potential location for hydrocarbon investigation. The information gained from the Paparoa Coal Measures can be applied to the Taranaki Basin, or other offshore Late Cretaceous rift basins in New Zealand, to gain a better understanding of the sediments given the lack of outcrop available in those basins.

References

Allen, P. A., & Allen, J. R. (1992). Basins due to lithospheric stretching. In: Allen PA, Allen JR 1992. Basin Analysis: Principles & Applications. Blackwell Scientific Publications. 43 – 92.

Allen, P. A., & Allen, J. R. (2013). Basin analysis: Principles and application to petroleum play assessment. John Wiley & Sons.

Adams, C. J. D, Harper, C. T., & Laird, M.G. (1975). K-AR ages of low grade metasediments of the Greenland and Waiuta Groups in Westland and Buller, New Zealand. *New Zealand Journal of Geology and Geophysics, v. 18*, p. 39-48.

Adams, C. J. D., & Nathan, S. (1978). Cretaceous chronology of the Lower Buller Valley, South Island, New Zealand. *New Zealand journal of geology and geophysics, 21*(4), 455-462.

Ahmed, S., Bhattacharya, J. P., Garza, D. E., & Li, Y. (2014). Facies architecture and stratigraphic evolution of a river-dominated delta front, Turonian Ferron Sandstone, Utah, USA. *Journal of Sedimentary Research, 84*(2), 97-121.

Arnott, R. W. C. (2010). Deep-marine sediments and sedimentary systems. *Facies models, 4*, 295-322.

Arribas, J., Critelli, S., & Johnsson, M. J. (Eds.). (2007). Sedimentary provenance and petrogenesis: perspectives from petrography and geochemistry. *Geological Society of America*, *420*

Bennett, P. C., Rogers, J. R., Choi, W. J., & Hiebert, F. K. (2001). Silicates, silicate weathering, and microbial ecology. *Geomicrobiology Journal, 18*(1), 3-19.

Barrier, A., Nicol, A., & Browne, G., (2017). Pre-rift reflectors within North Offshore Canterbury Basin, Western Edge of the Chatham Rise. Presented at Chatham Rise Workshop, GNS, Lower Hutt (New Zealand), 22-24 August, 2017.

Bassett, K., Ettmuller, F., & Bernet, M. (2006). Provenance analysis of the Paparoa and Brunner Coal Measures using integrated SEM-cathodoluminescence and optical microscopy. *New Zealand Journal of Geology & Geophysics, 49*, 241-254.

Bassett, K., Cody, E., Monteith, F., & Maitra, M. (2014). Greymouth coal field: a fault bounded basin, but which side. *Geoscience Society of New Zealand Annual Conference*. New Plymouth, New Zealand, 24-27 November, 2014.

Basset, K, Maitra, M., & Steadman, R. (2016). Enigmatic fitted clast textures, Cretaceous Paparoa Formation, Greymouth Basin. *Geoscience Society of New Zealand Annual Conference*. Wanaka, New Zealand, 28-1 December, 2016.

Basu, A., Young, S. W., Suttner, L. J., James, W. C., & Mack, G. H. (1975). Re-evaluation of the use of undulatory extinction and polycrystallinity in detrital quartz for provenance interpretation. *Journal of Sedimentary Research, 45*(4).

Basu, A. (1985). Reading provenance from detrital quartz. In Provenance of arenites, 231-247.

Beggs, J. M., Ghisetti, F. C., & Tulloch, A. J. (2008). Basin and petroleum systems analysis of the West Coast region, South Island, New Zealand. In PESA Eastern Australasian Basins Symposium III.

Bishop, D. J. (1992). Extensional tectonism and magmatism during the middle Cretaceous to Paleocene, North Westland, New Zealand. *New Zealand journal of geology and geophysics, 35*(1), 81-91.

Bowman, R. G. (1982). The Rapahoe Sector of the Greymouth Coalfield. New Zealand Coal Resources Survey Report, Ministry of Energy, Wellington, New Zealand. 84.

Bowman, R. G., Caffyn, P., Duff, S. W. (1984). Greymouth Coalfield. New Zealand Coal Resources Survey Report, Ministry of Energy, Wellington, New Zealand. Part 1, 211.

Boyd, R. J., Lewis, D. W. (1995). Sandstone diagenesis related to varying burial depth and temperature in Greymouth Coalfield, South Island, *New Zealand. New Zealand Journal of Geology and Geophysics 38*, 333-348.

Burbank, D. (1995). Tectonics of sedimentary basins (Vol. 579). C. J. Busby, & R. V. Ingersoll (Eds.). Oxford: Blackwell Science.

Chang, T. S., & Chun, S. S. (2012). Micro-characteristics of sustained, fine-grained lacustrine turbidites in the Cretaceous Hwangsan Tuff, SW Korea. *Geosciences Journal 16*: 409 – 420.

Chilingarian, G. V. (1964). Relationship between porosity, permeability and grainsize distribution of sands and sandstones. In: L. M. J. U. van Straaten (Ed.), Deltaic and Shallow Marine Deposits, Z. Elsevier Sci. Publ., Amsterdam, 1964, pp. 71-75.

Cody, E. (2015). *Sedimentology and Hydrocarbon Potential of the Paparoa Coal Measures Lacustrine Mudstones*. (Unpublished master's thesis). University of Canterbury, Christchurch, New Zealand.

Collinson, J. D. (1996). Alluvial sediments. *Sedimentary Environments: Process, Facies and Stratigraphy*, 37-82.

Condie, K. C., & Wronkiewicz, D. J. (1990). The Cr/Th ratio in Precambrian pelites from the Kaapvaal Craton as an index of craton evolution. *Earth and Planetary Science Letters, 97*(3-4), 256-267.

Condie, K. C. (1991). Another look at rare earth elements in shales. *Geochimica et Cosmochimica Acta, 55*(9), 2527-2531.

Connell, S. D. (2010). *Fluvial sedimentation in continental half-graben basins* (Unpublished doctoral thesis). Albuquerque, NM, University of New Mexico.

Cullers, R. L., Barrett, T., Carlson, R., & Robinson, B. (1987). Rare-earth element and mineralogic changes in Holocene soil and stream sediment: a case study in the Wet Mountains, Colorado, USA. *Chemical geology, 63*(3-4), 275-297.

Cullers, R. L., Basu, A., & Suttner, L. J. (1988). Geochemical signature of provenance in sand-size material in soils and stream sediments near the Tobacco Root batholith, Montana, USA. *Chemical Geology, 70*(4), 335-348.

Deer, W. A., Howie, R. A., & Zussman, J. (1992). *An introduction to the rock-forming minerals* (Vol. 2, p. 558). Harlow, England; Pearson Education Limited.

Dickinson, W. R., & Suczek, C. A. (1979). Plate tectonics and sandstone composition. *AAPG Bulletin, v. 63*, p. 2164-2182.

Dickinson, W. R., Beard, L. S., Brakenridge, G. R., Erjavec, J. L., Ferguson, R. C., Inman, K. F., Knepp, R. A., Lindberg, F. A., & Ryberg, P.T. (1983). Provenance of North American Phanerozoic sandstones in relation to tectonic setting. Geological Society of America Bulletin, v. 94, p. 222-235.

Dullien, F. A. (2012). *Porous media: fluid transport and pore structure*. Academic press.

Ebinger, C., & Scholz, C. A. (2012). Continental rift basins: the East African perspective. *Tectonics of Sedimentary Basins: Recent Advances*, 183-208.

Einsele, G. (1992). *Sedimentary basins: evolution, facies, and sedimentary budget*. Springer-Verlag.

Ellison, S. P. (1958). Origin of Porosity and Permeability. Lecture Notes, University of Texas, Austin, TX.

Frankenberger, A., Brooks, R. R., Varela-Alvarez, H., Collen, J. D., Filby, R. H., & Fitzgerald, S. L. (1994). Classification of some New Zealand crude oils and condensates by means of their trace element contents. *Applied geochemistry, 9*(1), 65-71.

Graton, L. C., & Fraser, H. J. (1935). Systematic packing of spheres: with particular relation to porosity and permeability. *The Journal of Geology, 43*(8, Part 1), 785-909.

Frisch, W., Meschede, M., & Blakey, R. (2011). Continental Graben Structures. *Plate Tectonics*, 27 – 41.

Gage, M. (1952). The Greymouth Coalfield. *New Zealand Geological Survey Bulletin 45*. 240 p.

Gaina, C., Müller, R. D., Roest, W. R., & Symonds, P. (1998). The opening of the Tasman Sea: a gravity anomaly animation. *Earth interactions, 2*(4), 1-23.

Gawthorpe, R. L., & Leeder, M. R. (2000). Tectono-sedimentary evolution of active extensional basins. *Basin Research 12,* 195 – 218.

Google earth pro. (2017, December 12). Lake Edward, [satellite], 30° 19’ 32.19” S, 29° 41’ 46.56” E. Retrieved from https://www.google.com/earth/.

Graham, I. J., & White, P. J. (1990). Rb-Sr dating of Rahu Suite granitoids from the Paparoa Range North Westland, New Zealand. *New Zealand journal of geology and geophysics, 33*(1), 11-22.

Grindley, G.W. (1961). Sheet 13, Golden Bay 1st ed., scale 1:250,000, Geological Map of New Zealand, Dep. Sci. Ind. Res., Wellington, New Zealand.

Hematite Petroleum, (1970). Haku-1 Well Report. Ministry of Economic Development. Unpublished Report.

Herd, M. E. J. (2007). *Continental Extensional Tectonics -The Paparoa Metamorphic Core Complex of Westland, New Zealand* (Unpublished master’s thesis). University of Canterbury, Christchurch, New Zealand.

Higgs, K. E., Zwingmann, H., Reyes, A. G., & Funnell, R. H. (2007). Diagenesis, porosity evolution, and petroleum emplacement in tight gas reservoirs, Taranaki basin, New Zealand. *Journal of Sedimentary Research, 77*, 1003-1025.

Higgs, K. E., Arnot, M. J., Brown, G. H., & Kennedy, E. M. (2010). Reservoir potential of Late Cretaceous terrestrial to shallow marine sandstones, Taranaki Basin, New Zealand. *Marine and petroleum Geology, 27*, 1849-1871

Higgs, K. E., King, P. R., Raine, J. I., Sykes, R., Browne, G. H., Crouch, E. M., & Baur, J. R. (2012). Sequence stratigraphy and controls on reservoir sandstone distribution in an Eocene marginal marine-coastal plain fairway, Taranaki Basin, New Zealand. *Marine and petroleum geology, 32*(1), 110-137.

Hirner, A. V., & Lyon, G. L. (1989). Stable isotope geochemistry of crude oils and of possible source rocks from New Zealand—1: carbon. *Applied geochemistry, 4*(2), 109-120.

Horton, B. K. (1998). Sediment accumulation on top of the Andean orogenic wedge: Oligocene to late Miocene basins of the Eastern Cordillera, southern Bolivia. *Geological Society of America Bulletin, 110*(9), 1174-1192.

Houghton, H. F. (1980). Refined techniques for staining plagioclase and alkali feldspars in thin section. *Journal of Sedimentary Research, 50*(2), 629-631.

Houseknecht, D. W. (1987). Assessing the relative importance of compaction processes and cementation to reduction of porosity in sandstones. *AAPG bulletin, 71*(6), 633-642.

Ingersoll, R. V., Bullard, T. F., Ford, R. L., Grimm, J. P., Pickle, J. D., & Sares, S. W. (1984). The effect of grain size on detrital modes: a test of the Gazzi-Dickinson point-counting method. *Journal of Sedimentary Research, 54*(1), 103-116.

Johnsson, M. J., & Basu, A. (1993). Processes controlling the composition of clastic sediments (Vol. 284). Geological Society of America.

Jones, H. L., & Hajek, E. A. (2007). Characterizing avulsion stratigraphy in ancient alluvial deposits. *Sedimentary Geology*, 202(1), 124-137.

Kelts, K. (1988). Environments of deposition of lacustrine petroleum source rocks: an introduction. In: Fleet AJ, Kelts K, Talbot MR 1988. Lacustrine petroleum source rocks. *Geological Society special publication 40*, 3 – 26.

Kimbrough, D. L., & Tulloch, A. J. (1989). Early Cretaceous age of orthogneiss from the Charleston Metamorphic Group, New Zealand. *Earth and planetary science letters, 95*(1), 130-140.

King, P. R., & Thrasher, G. P. (1996). Cretaceous Cenozoic geology and petroleum systems of the Taranaki Basin, New Zealand (Vol. 2). Institute of Geological & Nuclear Sciences.

Laird, M. G. (1968). The Paparoa tectonic zone. *New Zealand journal of geology and geophysics, 11*(2), 435-454.

Laird, M. G. (1972). Sedimentology of the Greenland Group in the Paparoa Range, West Coast, South Island. *New Zealand journal of geology and geophysics, 15*(3), 372-393.

Laird, M.G., Shelley, D. (1974). Sedimentation and early tectonic history of the Greenland Group, Reefton, New Zealand. *New Zealand Journal of Geology and Geophysics, 17*, 839-854.

Laird, M. (1993). Cretaceous continental rifts: New Zealand region. In: Ballance PF ed. *South Pacific sedimentary basins: sedimentary basins of the world 2*. Amsterdam, NL, Elsevier Science Publishers B.V. Pp. 37-49.

Laird, M. (1994). Geological aspects of the opening of the Tasman Sea. In: van der Lingen GJ, Swanson KM, Muir RJ ed. *Evolution of the Tasman Sea Basin*. Rotterdam, Netherlands, A. A. Balkema. Pp. 1-17.

Laird, M. G., & Bradshaw, J. D. (2004). The break-up of a long-term relationship: the Cretaceous separation of New Zealand from Gondwana. *Gondwana Research, 7*(1), 273-286

Le Bas, M. L., Maitre, R. L., Streckeisen, A., Zanettin, B., & IUGS Subcommission on the Systematics of Igneous Rocks. (1986). A chemical classification of volcanic rocks based on the total alkali-silica diagram. *Journal of petrology, 27*(3), 745-750.

Leeder, M. R., & Gawthorpe, R. L. (1987). Sedimentary models for extensional tilt-block/half-graben basins. *Geological Society, London, Special Publications, 28*(1), 139-152.

Leeder, M. R. (1995). Continental Rifts and Proto-Oceanic Rift Troughs. In: Busby CJ, Ingersoll RV 1995. *Tectonics of Sedimentary Basins*. Blackwell Science. 119 – 148.

Leeder, M. R. (1999). Sedimentology in Sedimentary Basins. In: Leeder MR, *Sedimentology and Sedimentary Basins: From Turbulence to Tectonics*. Blackwell Science. 497 – 530.

Lewis, D. W., & McConchie, D, (1994). *Practical sedimentology (2nd ed)*. Chapman and Hall, New York

Li, Z. (2002). Mineralogy and trace elements of the Cretaceous Greymouth coals and their combustion products (Unpublished doctoral thesis). University of Canterbury, Christchurch, New Zealand.

Loucks, R. G., Reed, R. M., Ruppel, S. C., & Hammes, U. (2012). Spectrum of pore types and networks in mudrocks and a descriptive classification for matrix-related mudrock pores. *AAPG bulletin, 96*(6), 1071-1098.

Lundegard, P. D. (1992). Sandstone Porosity Loss. *Journal of Sedimentary Research, 62*(2).

Maitra, M. K., Bassett, K., Nicol, A., & Sykes, R. (2016). Sequence stratigraphy and subsidence analysis of Late Cretaceous-Paleocene lacustrine source rocks, Greymouth Coalfield basin. New Zealand Petroleum Conference. Auckland, New Zealand, 21-23 March, 2016.

Maitra, M. K., & Bassett, K. (2016). Sedimentary facies analysis and sequence stratigraphy of the Paparoa Coal Measures, Greymouth Basin, New Zealand. Geoscience Society of New Zealand Annual Conference. Wanaka, New Zealand, 28-1 December, 2016.

Maitra, M. K., & Bassett, K. (2017a). Detailed facies analysis and sequence stratigraphy of potential lacustrine source rocks, Greymouth Basin, New Zealand. Calgary Geoconvention, Canada, 15-19 May, 2017.

Maitra, M. K., & Bassett, K. (2017b). Facies analysis of the lacustrine source rocks of the Greymouth Basin; A combined study of cores, outcrops and geophysical logs. New Zealand Petroleum Conference. New Plymouth, New Zealand, 21-23 March, 2016.

Maitra, M. K., & Bassett, K. (2017c). Tectonic Evolution of the Late Cretaceous to early Palaeocene Greymouth Basin, West Coast. Geoscience Society of New Zealand Annual Conference. Wanaka, New Zealand, 28-1 December, 2017.

Maitra, M. K., & Bassett, K. (2018). Applying sequence stratigraphic concepts to the distribution of potential source rocks of the Greymouth Basin. New Zealand. New Zealand Petroleum Conference. Wellington, New Zealand, 26-28 March, 2018.

Makaske, B., Smith, D. G., & Berendsen, H. J. (2002). Avulsions, channel evolution and floodplain sedimentation rates of the anastomosing upper Columbia River, British Columbia, Canada. *Sedimentology, 49*(5), 1049-1071.

Matthews, E.R. (1990). Exploration in the onshore Westland basin. 1989 New Zealand oil exploration conference proceedings 1. Wellington, Energy & Resources Division, Ministry of Commerce. Pp. 62-69.

Mathieu, L., de Vries, B. V. W., Pilato, M., & Troll, V. R. (2011). The interaction between volcanoes and strike-slip, transtensional and transpressional fault zones: Analogue models and natural examples. *Journal of Structural Geology, 33*(5), 898-906.

Middelburg, J. J., van der Weijden, C. H., & Woittiez, J. R. (1988). Chemical processes affecting the mobility of major, minor and trace elements during weathering of granitic rocks. *Chemical Geology, 68*(3), 253-273.

McLennan, S. M., Taylor, S. R., McCulloch, M. T., & Maynard, J. B. (1990). Geochemical and Nd, Sr isotopic composition of deep-sea turbidites: Crustal evolution and plate tectonic associations. *Geochimica et Cosmochimica Acta, 54*(7), 2015-2050.

McLennan, S. M., & Taylor, S. R. (1991). Sedimentary rocks and crustal evolution: tectonic setting and secular trends. *The Journal of Geology, 99*(1), 1-21.

McNee, J. T. (1997). *Structural geology of the Rapahoe Sector, Greymouth coalfield, West Coast, New Zealand* (Unpublished masters thesis). University of Canterbury, Christchurch, New Zealand.

Morgan, P.G. (1911) The geology of the Greymouth Subdivision, North Westland. *New Zealand Geological Survey Bulletin 13*.

Mortimer, N., Rattenbury, M. S., King, P. R., Bland, K. J., Barrell, D. J. A., Bache, F., & Edbrooke, S. W. (2014). High-level stratigraphic scheme for New Zealand rocks. *New Zealand Journal of Geology and Geophysics*, *57*(4), 402-419.

Muir, R. J., Ireland, T. R, Weaver, S. D. & Bradshaw, J. D. (1992) "Ion Microprobe (SHRIMP) U Pb Zircon Dating of Western Province Granitoids." In Nobes, D.C. (editor) (1992) "Geological Society of New Zealand and New Zealand Geophysical Society 1992 joint annual conference." *Geological Society of New Zealand Miscellaneous Publication*. 63A; 110 pp.

Muir, R. J., Ireland, T. R., Weaver, S. D., & Bradshaw, J. D. (1994). Ion microprobe U & Pb zircon geochronology of granitic magmatism in the Western Province of the South Island, New Zealand. *Chemical geology*, *113*(1-2), 171-189.

Muir, R. J., Weaver, S. D., Bradshaw, J. D., Eby, G. N., Evans, J. A., & Ireland, T. R. (1996). Geochemistry of the Karamea Batholith, New Zealand and comparisons with the Lachlan fold belt granites of SE Australia. *Lithos, 39*(1), 1-20.

Nathan, S. (1978). Sheet S44—Greymouth. Geological map of New Zealand 1:63 360. Lower Hutt, New Zealand, Department of Scientific and Industrial Research.

Nathan, S., Anderson, H. J., Cook, R. A., Herzer, R. H., Hoskins, R. H., Raine, J. I. & Smale, D. (eds) (1986). Cretaceous and Cenozoic sedimentary basins of the West Coast region, South Island. *New Zealand Geological Survey Basin Studies, 1*. New Zealand Department of Scientific and Industrial Research, Wellington.

Nathan, S., Rattenbury, M. S. & Suggate, R. P. (compilers) (2002). Geology of the Greymouth area: scale 1:250,000. Lower Hutt: Institute of Geological & Nuclear Sciences. Institute of Geological & Nuclear Sciences 1:250,000 geological map 12. 58 p. + 1 folded map

Nesbitt, H. W. (1979). Mobility and fractionation of rare earth elements during weathering of a granodiorite. *Nature, 279*(5710), 206-210.

Newman, J. (1985). *Palaeoenvironment, coal properties and their interrelationship in Paparoa and selected Brunner Coal Measures on the West Coast of South Island* (Unpublished doctoral thesis). University of Canterbury, Christchurch, New Zealand.

Newman, J., Newman. N.A. (1992). Tectonic and paleoenvironmental controls on the distribution and properties of Upper Cretaceous coals on the West Coast of the South Island, New Zealand. *Geological Society of America Special Paper 267*, 347-368.

Nunweek, C. N. (2001). *Depositional controls on peat accumulation and coal characteristics, Dunollie and Brunner coal measures, Southern Rapahoe Sector, Greymouth* (Unpublished masters thesis). University of Canterbury, Christchurch, New Zealand.

Petroleum Basin Explorer (PBE), GNS Science. Accessed from http://data.gns.cri.nz/pbe/index.html#HTML:Content/PBE_Home.html.

Peterson, J. A. (2009). *Geochemical provenance of clastic sedimentary rocks in the Western Cordillera: Utah, Colorado, Wyoming, and Oregon*. Utah State University.

Pettijohn, F. J., Potter, P. E., & Siever, R. (1972). Sand and sandstone. *Bedin: Springer-Verlag*, *62*.

Phillips, W. R., & Griffen, D. T. (1981). *Optical mineralogy: the nonopaque minerals*. WH Freeman.

Potter, P. E., Maynard, J. B., & Depetris, P. J. (2005). *Mud and mudstones: Introduction and overview*. Springer Science & Business Media.

Reineck, H. E., & Singh, I. B. (2012). *Depositional sedimentary environments: with reference to terrigenous clastics*. Springer Science & Business Media.

Roex, A. P., Späth, A., & Zartman, R. E. (2001). Lithospheric thickness beneath the southern Kenya Rift: implications from basalt geochemistry. *Contributions to Mineralogy and Petrology, 142*(1), 89-106.

Roser, B. P., Cooper, R. A., Nathan, S., & Tulloch, A. J. (1996). Reconnaissance sandstone geochemistry, provenance, and tectonic setting of the lower Paleozoic terranes of the West Coast and Nelson, New Zealand. *New Zealand Journal of Geology and Geophysics*, *39*(1), 1-16.

Ruzyla, K., & Jezek, D. I. (1987). Staining method for recognition of pore space in thin and polished sections. Journal of Sedimentary Research, 57(4).

Sagar, M. W., & Palin, J. M. (2011). Emplacement, metamorphism, deformation and affiliation of mid-Cretaceous orthogneiss from the Paparoa Metamorphic Core Complex lower-plate, Charleston, New Zealand. *New Zealand Journal of Geology and Geophysics*, *54*(3), 273-289.

Sagar, M. W., & Palin, J. M. (2013). Carboniferous U–Pb zircon age for S-type Karamea Suite Redjacket Granite, Paparoa Metamorphic Core Complex lower plate, northern Westland. *New Zealand Journal of Geology and Geophysics*, *56*(3), 109-120.

Sara, W. A. (1963). Reserves of bituminous coal in the Liverpool and Paparoa areas, Greymouth coalfield. *New Zealand Journal of Geology and Geophysics*, *6*(4), 566-581.

Schulte, D. O., Ring, U., Thomson, S. N., Glodny, J., & Carrad, H. (2014). Two-stage development of the Paparoa metamorphic core complex, West Coast, South Island, New Zealand: Hot continental extension precedes sea-floor spreading by~ 25 my. *Lithosphere*, *6*(3), 177-194.

Strogen, D. P., Seebeck, H., Nicol, A., & King, P. R. (2017). Two-phase Cretaceous–Paleocene rifting in the Taranaki Basin region, New Zealand; implications for Gondwana break-up. *Journal of the Geological Society*, jgs2016-160.

Strong, D. T., Turnbull, R. E., Haubrock, S., & Mortimer, N. (2016). Petlab: New Zealand's national rock catalogue and geoanalytical database. *New Zealand Journal of Geology and Geophysics, 59*(3), 475-481.

Suggate, R. P. (2013). Late Cretaceous and Paleogene stratigraphy and structure linking offshore with onshore north Westland, New Zealand. *New Zealand Journal of Geology and Geophysics, 56*(4), 263-275.

Suggate, R. P. (2015). Extensional basin development and subsequent inversion in Greymouth Coalfield. *New Zealand Journal of Geology and Geophysics, 58(*1), 1-12.

Sun, S. S., & McDonough, W. S. (1989). Chemical and isotopic systematics of oceanic basalts: implications for mantle composition and processes. *Geological Society, London, Special Publications, 42*(1), 313-345.

Sykes, R., Volk, H., George, S. C., Ahmed, M., Higgs, K. E., Johansen, P. E., & Snowdon, L. R. (2014). Marine influence helps preserve the oil potential of coaly source rocks: Eocene Mangahewa Formation, Taranaki Basin, New Zealand. *Organic Geochemistry, 66*, 140-163.

Tatar, O., Yurtmen, S., Temiz, H., Guersoy, H., Kocbulut, F., Mesci, B. L., & Guezou, J. C. (2007). Intracontinental Quaternary Volcanism in the Niksar Pull-Apart Basin, North Anatolian Fault Zone, Turkey. *Turkish Journal of Earth Sciences, 16*(4), 417-440.

Tiab, D., & Donaldson, E. C. (2015). *Petrophysics: theory and practice of measuring reservoir rock and fluid transport properties*. Gulf professional publishing.

Tulloch, A. J. (1973). The Barrytown adamellite stock and its contact aureole (Unpublished bachelor of science honours thesis). University of Canterbury, Christchurch, New Zealand.

Tulloch, A. J. (1983). Granitoid rocks of New Zealand—a brief review. *Geological Society of America Memoirs*, *159*, 5-20.

Tulloch, A. J., & Brathwaite, R. L. (1986). Granitoid rocks and associated mineralisation of Westland-west Nelson, New Zealand. *New Zealand Geological Survey record, 13*, 65-92.

Tulloch, A. J., & Kimbrough, D. L. (1989). The paparoa metamorphic core complex, New Zealand: cretaceous extension associated with fragmeotation of the Pacific margin of Gondwana. *Tectonics*, *8*(6), 1217-1234.

Tulloch, A. J., Kimbrough, D. L., & Waight, T.E. (1992). The Brunner granite, north Westland : Late Cretaceous A - type plutonism on the Tasman passive margin. p. 153 IN: Nobes, D.C. (ed.) Geological Society of New Zealand and New Zealand Geophysical Society 1992 joint annual conference, University of Canterbury, 23 November - 27 November : programme and abstracts. Lower Hutt, NZ: Geological Society of New Zealand. Geological Society of New Zealand miscellaneous publication 63A. See: p. 153 Note: Review, Abstract

Tulloch, A. J., Ramezani, J., Kimbrough, D. L., Faure, K., & Allibone, A. H. (2009). U-Pb geochronology of mid-Paleozoic plutonism in western New Zealand: Implications for S-type granite generation and growth of the east Gondwana margin. *Geological Society of America Bulletin*, B26272-1.

Türkmen, İ., Aksoy, E., & Taşgin, C. K. (2007). Alluvial and lacustrine facies in an extensional basin: The Miocene of Malatya basin, eastern Turkey. *Journal of Asian Earth Sciences, 30*(1), 181-198.

Uruski, I. C. (2008). Deepwater Taranaki, New Zealand: structural development and petroleum potential. *Exploration geophysics, 39*(2), 94-107.

Waight, T. E., Weaver, S. D., & Muir, R. J. (1998). Mid-Cretaceous granitic magmatism during the transition from subduction to extension in southern New Zealand: a chemical and tectonic synthesis. *Lithos, 45*(1), 469-482.

Ward, S. D. (1997). Lithostratigraphy, palynostratigraphy and basin analysis of the Late Cretaceous to early Tertiary Paparoa Group, Greymouth Coalfield, New Zealand (Unpublished doctoral thesis). University of Canterbury, Christchurch, New Zealand.

Weltje, G. J., & von Eynatten, H. (2004). Quantitative provenance analysis of sediments: review and outlook. *Sedimentary Geology, 171*(1), 1-11.

Wiltshire, M. J. (1984). Well Completion Report, Kongahu-1. PPL38058, Offshore, West Coast, South Island NZ. Ministry of Economic Development New Zealand. Unpublished Report

Winchester, J. A., & Floyd, P. A. (1977). Geochemical discrimination of different magma series and their differentiation products using immobile elements. *Chemical geology*, *20*, 325-343.

Winter, J.D. (2010) *Principles of Igneous and metamorphic petrology*. Whitman College, Washington, USA.

Yan, Y., Xia, B., Lin, G., Cui, X., Hu, X., Yan, P., & Zhang, F. (2007). Geochemistry of the sedimentary rocks from the Nanxiong Basin, South China and implications for provenance, paleoenvironment and paleoclimate at the K/T boundary. *Sedimentary Geology, 197*(1), 127-140.

Yanguas, J. E., & Dravis, J. J. (1985). Blue fluorescent dye technique for recognition of microporosity in sedimentary rocks. *Journal of Sedimentary Research, 55*(4).

Young, D. J. (1967). Oil-bearing paparoa coal measures near Rewanui, Greymouth coalfield. *New Zealand Journal of Geology and Geophysics*, *10*(3), 666-674.

Zink, K. G., & Sykes, R. (2015). *Geochemical database and interpretation of 10 oils from several New Zealand basins*. GNS Science.

Appendices

Clast Count Localities and Depth

12 Mile Beach Clast Counts				
GPS		Contact	Formation	
S	E			
42.19'02.7	171.16'33.3E	Sharp & Erosional	Greenland Group - Morgan Contact	
42.19'06.18	171.16'28.0	Sharp & Erosional	Greenland Group - Morgan Contact	
42.19'05.11	171.16'30.9		Mid Morgan	
42.19'12.2	171.16'46.9		Morgan - Waiomo Contact	
42.19'19.4179	171.16'13.1572	Gradational/Sharp	Rewanui - Waiomo Contact	
42.19'19.4180	171.16'13.1573		Rewanui	
42.19'30.4416	171.16'0.1259		Rewanui	
42.19'39.1071	17115'56.9901		Rewanui	
42.19'48.1	171.15'52.0		Rewanui	
42.19'53.75	171.15'48.1		Rewanui	
42.20'01.9	171.15'39.5		Dunollie	
42.20'05.9	171.15'38.1		Bleached Dunollie	
Core Clast Counts				
Drill Hole	Depth From (m)	Depth To (m)	Formation	Log Quality
620	798.3	800.9	Jay	Log Good
620	794.26	797.26	Jay	Log Good
620	772.7	774.9	Morgan	Log Good

Drill Hole	Depth From (m)	Depth To (m)	Formation	Log Quality
634	556	559.3	Rewanui	Log Good
634	510.2	512.8	Rewanui	Log Good
634	495.5	503.8	Rewanui	Log Good
634	489.9	491.4	Rewanui	Log Good
634	480.2	488.8	Rewanui	Log Good
634	476.7	477	Rewanui	Log Good
634	470.9	475.2	Rewanui	Log Good
634	468.7	469.7	Rewanui	Log Good
634	458.4	466.3	Rewanui	Log Good
634	455.6	457.2	Rewanui	Log Good
634	449.8	452.4	Rewanui	Log Good
634	443	448.7	Rewanui	Log Good
634	391.8	442	Rewanui	Log Good
634	380.6	385.1	Rewanui	Log Good
634	363.7	373.3	Dunollie	Log Good
634	347.2	360.7	Dunollie	Log Good
634	317.3	342.7	Dunollie	Log Good
634	311.7	316.4	Dunollie	Log Good
660	436	478	Jay	Log Good
649	376.5	376.9	Jay	Log Good
				Log Good
632	670.2	670.5	Jay	Log Good
632	559	561.2	Rewanui	Log Good
632	496.9	499.2	Rewanui	Log Good
632	489.8	490.3	Rewanui	Log Good
632	431.7	432.3	Rewanui	Log Good
632	430.3	430.8	Rewanui	Log Good

Drill Hole	Depth From (m)	Depth To (m)	Formation	Log Quality
632	402.3	404.3	Rewanui	Log Good
632	401.1	401.3	Rewanui	Log Good
		Morgan Volcanics		
GPS		Contact	Formation	
S	E			
42°21'49.53	171°22'18.25	Location 1	Morgan Volcanics	
		Location 2	Morgan Volcanics	
		Location 3	Morgan Volcanics	

Core Sample Localities and Depth

Well / Drill hole	Sample Type	Sample	From Depth (m)	To Depth (m)	Formation
620	Clast Sample	1	774.1	774.2	Jay
620	Clast Sample	2	796.57	796.67	Jay
620	Clast Sample	3	800.78	800.92	Jay
634	Clast sample	4	557.2	557.3	Rewanui
634	Clast Sample	5	556.5	556.6	Rewanui
634	Clast sample	6	495.9	495.95	Rewanui
634	Clast sample	7	512.08	512.12	Rewanui
634	Clast sample	12	484.25	484.28	Rewanui
634	Clast sample	8	491.2	491.25	Rewanui
634	Clast sample	14 a	487.4	487.5	Rewanui
634	Clast sample	9	491	491.05	Rewanui
634	Clast sample	10	490.3	490.35	Rewanui
634	Clast sample	13	484.85	484.95	Rewanui
634	Clast sample	11	484.2	484.22	Rewanui
634	Clast sample	15 a	488.6	488.66	Rewanui
634	Clast sample	14 b	484.25	484.28	Rewanui
634	Sandstone Sample	15 b	310.41	315.41	Dunollie
634	Sandstone Sample	16	549.95	549.9	Rewanui
634	Sandstone Sample	17	536.42	536.47	Rewanui
634	Sandstone Sample	18	526.44	526.49	Rewanui
634	Sandstone Sample	19	518.45	518.4	Rewanui
634	Clast sample	20	465.61	465.66	Rewanui
634	Clast Sample	21	404.1	404.05	Rewanui
634	Sandstone Sample	22	391.66	391.62	Rewanui
634	Clast Sample	23	384.86	384.81	Rewanui

Well / Drill hole	Sample Type	Sample	From Depth (m)	To Depth (m)	Formation
634	Clast Sample	24	384.36	348.31	Dunollie
660	Clast Sample	25	470	471	Jay
660	Sandstone Sample	26	433.6	433.65	Jay
660	Sandstone Sample	27	253.3	253.6	Morgan
660	Sandstone Sample	28	242.1	242.15	Morgan
660	Sandstone Sample	29	86	86.5	Rewanui
660	Sandstone Sample	30	86.6	86.5	Rewanui
660	Sandstone Sample	31	88	88.05	Rewanui
660	Sandstone Sample	32	89.1	89.15	Rewanui
660	Sandstone Sample	33	91.75	91.8	Rewanui
660	Sandstone Sample	34	95.9	95.95	Rewanui
660	Sandstone Sample	35	98.7	98.75	Rewanui
660	Sandstone Sample	36	102.6	102.65	Rewanui
660	Sandstone Sample	37	105.6	105.65	Rewanui
660	Sandstone Sample	38	107.6	107.65	Rewanui
660	Sandstone Sample	39	109.7	109.75	Rewanui
660	Sandstone Sample	40	113.5	113.55	Rewanui
660	Sandstone Sample	41	117.45	117.5	Rewanui
660	Sandstone Sample	42	118.25	118.3	Rewanui
660	Sandstone Sample	43	121.35	121.4	Rewanui
660	Sandstone Sample	44	124.65	124.7	Rewanui
660	Sandstone Sample	45	126.05	126.1	Rewanui
660	Sandstone Sample	46	130.3	130.35	Rewanui
660	Sandstone Sample	47	1318	1318.05	Rewanui
660	Sandstone Sample	48	136.1	136.15	Rewanui
660	Sandstone Sample	49	137.2	137.25	Rewanui
660	Sandstone Sample	50	149.8	149.85	Rewanui
660	Sandstone Sample	51	152.55	152.6	Rewanui

Well / Drill hole	Sample Type	Sample	From Depth (m)	To Depth (m)	Formation
660	Sandstone Sample	52	153.65	153.7	Rewanui
660	Sandstone Sample	53	158.3	158.35	Rewanui
660	Sandstone Sample	54	158.5	158.55	Rewanui
660	Sandstone Sample	56	158.9	158.95	Rewanui
660	Sandstone Sample	57	159.1	159.15	Rewanui
660	Sandstone Sample	58	161.5	161.55	Rewanui
660	Sandstone Sample	59	164.9	164.95	Rewanui
660	Sandstone Sample	60	167.8	167.85	Rewanui
660	Sandstone Sample	61	178.8	178.85	Rewanui
660	Sandstone Sample	62	181.6	181.65	Rewanui
660	Sandstone Sample	63	183.5	183.55	Rewanui
660	Sandstone Sample	64	184.9	184.95	Rewanui
660	Sandstone Sample	65	185.8	185.85	Rewanui
649	Clast Sample	67	376.65	376.7	Rewanui
649	Sandstone Sample	68	346.4	346.45	Rewanui
649	Sandstone Sample	69	336.2	336.25	Rewanui
649	Sandstone Sample	70	333	333.05	Rewanui
649	Sandstone Sample	71	267.1	267.15	Dunollie
649	Cuttings	72	113	138	Brunner cuttings
632	Clast Sample	73	670.25	670.3	Rewanui
632	Clast Sample	74	560.2	560.25	Rewanui
632	Clast Sample	75	560.5	560.55	Rewanui
632	Sandstone Sample	76	546.4	546.45	Rewanui
632	Sandstone Sample	77	533.6	533.65	Rewanui
632	Sandstone Sample	78	489.1	489.15	Rewanui
632	Sandstone Sample	79	465.9	465.95	Rewanui
632	Sandstone Sample	80	461.7	461.75	Rewanui

Well / Drill hole	Sample Type	Sample	From Depth (m)	To Depth (m)	Formation
632	Sandstone Sample	81	458	458.05	Rewanui
632	Sandstone Sample	82	455.5	455.55	Rewanui
632	Sandstone Sample	83	447.1	447.15	Rewanui
632	Sandstone Sample	84	415.78	415.83	Rewanui
632	Sandstone Sample	85	399.4	399.45	Rewanui
632	Sandstone Sample	86	386.64	386.69	Rewanui
632	Sandstone Sample	87	385.99	386.04	Rewanui
632	Sandstone Sample	88	379.28	379.33	Rewanui
632	Sandstone Sample	89	369.64	369.69	Rewanui
632	Sandstone Sample	90	353.52	353.57	Rewanui
632	Sandstone Sample	91	350.6	350.65	Rewanui
632	Sandstone Sample	92	348.2	348.25	Rewanui
632	Sandstone Sample	93	318.9	318.95	Rewanui
632	Sandstone Sample	94	290.95	291	Rewanui
632	Sandstone Sample	95	279.8	279.85	Rewanui
632	Sandstone Sample	96	275.5	275.55	Rewanui
632	Sandstone Sample	97	274.3	274.35	Rewanui
632	Sandstone Sample	98	257.3	257.35	Rewanui

Outcrop Sample Localities

Field Samples	Descriptions	South	East	Formation
12 Mile Beach				
12MA01	Greenland Group Clast	42.19'02.7	171.16'33.3	Morgan
12MA02	Hornfels Clast	42.19'02.7	171.16'33.3	Morgan
12MA03	Quartz Clast	42.19'02.7	171.16'33.3	Morgan
12MA04	Aplite Clast	42.19'02.7	171.16'33.3	Morgan
12MB01	Basalt Clast	42.19'20.05	171.16'36.28	Rewanui
12MB02	Granite (weathered) Clast	42.19'19'41	171.16'13.25	Rewanui
12MB03	Granite (weathered) Clast	42.19'19'42	171.16'13.26	Rewanui
12MB04	Hornfels Clast	42.19'19'43	171.16'13.27	Rewanui
12MB05	Greenland Group Clast	42.19'19'41	171.16'13.25	Rewanui
12MB06	Aplite Clast	42.19'19'42	171.16'13.26	Rewanui
12MB07	Suspected Basalt/Hornfels Clast	42.19'19'43	171.16'13.27	Rewanui
12MB08	Quartz Clast	42.19'19'41	171.16'13.25	Rewanui
12MB09	Sandstone Sample	42.19'19'42	171.16'13.26	Rewanui
12MC01	Waiomo Mudstone Clast	42.19'19'41	171.16'13.25	Rewanui
12MC02	Greenland Group Clast	42.19'19'42	171.16'13.26	Rewanui
12MC03	Aplite Clast	42.19'19'41	171.16'13.25	Rewanui
12MC04	Basalt Clast	42.19'19'42	171.16'13.26	Rewanui
12MD01	Sandstone Sample	42.19'58.24	171.15'42.98	Rewanui
12ME01	Sandstone Sample	42.19'58.24	171.15'42.98	Rewanui
12MF01	Waiomo Formation (Mudstone)	42.19'7.0483	171.16'27.2857	Waiomo
12MF02	Waiomo Formation (Mudstone)	42.19'11.7581	171.16'26.0584	Waiomo
12MF03	Waiomo Formation (Mudstone)	42.19'13.5980	171.16'23.1674	Waiomo
12MG01	Hornfels Clast	42.20'3.6620	171.15'38.1794	Dunollie
12MG02	Greenland Group Clast	42.20'3.6621	171.15'38.1795	Dunollie

Field Samples	Descriptions	South	East	Formation
7 Mile Creek				
7M01	Goldlight Formation (Mudstone)	42.23'16.3840	171.17'7.7897	Goldlight
7M02	Goldlight Formation (Mudstone)	42.23'16.04425	171.16'47.5713	Goldlight
7M03	Goldlight Formation (Mudstone)	42.23'20.64725	171.16'32.1646	Goldlight
Blackball Paparoa Creek				
BB01	Basalt Clast	42°21'49.53"S	171°22'18.25"E	Morgan Volcanics
BB02	Basalt Clast	42°21'49.53"S	171°22'18.25"E	Morgan Volcanics
BB03	Basalt Clast	42°21'49.53"S	171°22'18.25"E	Morgan Volcanics
BB04	Basalt Clast	42°21'49.53"S	171°22'18.25"E	Morgan Volcanics
BB05	Basalt Clast	42°21'49.53"S	171°22'18.25"E	Morgan Volcanics
BB06	Basalt Clast	42°21'49.53"S	171°22'18.25"E	Morgan Volcanics
BB07	Basalt Clast	42°21'49.53"S	171°22'18.25"E	Morgan Volcanics
BB08	Basalt Clast	42°21'49.53"S	171°22'18.25"E	Morgan Volcanics
BB09	Basalt Clast	42°21'49.53"S	171°22'18.25"E	Morgan Volcanics
Basalt Samples				
1	Hornfels Clast	42.19'19.58	171.16'13.35	Rewanui
2	Hornfels Clast	42.19'19.58	171.16'13.35	Rewanui
3	Hornfels Clast	42.19'19.62	171.16'13.48	Rewanui
4	Hornfels Clast	42.19'19.58	171.16'16.43	Rewanui
5	Basalt Clast	42.19'19.42	171.16'13.26	Rewanui
6	Hornfels Clast	42.19'19.63	171.16'13.48	Rewanui
7	Hornfels Clast	42.19'20.42	171.16'46.26	Rewanui
8	Basalt Clast	42.19'19.57	171.16'58.24	Rewanui
9	Basalt Clast	42.19'36.12	171.16'13.26	Rewanui

Geochemical Analysis Results

SPECTRACHEM ANALYTICAL

CRL Energy Ltd

UNIVERSITY OF CANTERBURY

JOB REFERENCE: SA19661

MAJOR OXIDE ANALYSES

SAMPLE	SCA	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	LOI	SUM
Sample # 1	**1**	66.87	0.71	15.17	5.88	0.07	3.04	0.32	0.83	2.01	0.02	1.78	96.72
Sample # 2	**2**	71.60	0.83	13.53	4.23	0.03	2.78	0.36	1.06	0.17	0.02	1.42	96.03
Sample # 3	**3**	68.13	0.66	15.60	4.18	0.06	2.78	0.47	0.91	1.83	0.06	1.74	96.41
Sample # 4	**4**	73.16	0.67	13.01	3.45	0.05	2.27	0.40	0.75	1.68	0.06	1.54	97.04
Sample # 5	**5**	55.12	0.87	21.40	6.91	0.06	4.62	0.70	1.54	0.14	0.03	2.04	93.42
Sample # 6	**6**	74.66	0.61	12.79	2.12	0.06	1.46	0.24	0.24	4.67	0.17	2.11	99.13
Sample # 7	**7**	67.11	0.73	15.54	5.01	0.05	3.00	0.80	1.01	0.59	0.20	1.67	95.70
Sample # 8	**8**	57.32	0.80	20.59	7.08	0.07	3.86	0.63	1.36	0.24	0.03	1.96	93.94
Sample # 9	**9**	55.50	0.79	21.41	6.96	0.09	4.36	0.56	1.57	0.13	0.03	1.96	93.36

SAMPLE	SCA	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	LOI	SUM
Sample # 12	**10**	57.94	0.10	14.57	8.89	0.25	2.32	1.28	0.20	4.03	0.11	10.28	99.98
Sample # 14	**11**	69.38	0.08	15.73	2.98	0.09	0.73	0.63	0.19	4.50	0.20	5.24	99.76
Sample # 15	**12**	72.57	0.05	16.62	1.10	0.05	0.24	0.39	0.20	4.58	0.19	3.83	99.82
Sample # 20	**13**	71.54	0.05	16.65	1.09	0.05	0.25	1.00	0.20	4.46	0.67	3.88	99.84
Sample # 21	**14**	71.86	0.06	15.63	1.06	0.08	0.33	0.64	0.21	5.01	0.20	4.48	99.56
Sample # 23	**15**	73.13	0.07	16.37	0.82	0.04	0.16	0.28	0.21	4.82	0.22	3.73	99.86
12MF01	**16**	77.89	1.13	10.81	2.70	0.01	1.25	0.07	0.26	2.22	0.04	3.69	100.06
12MF02	**17**	67.02	0.79	16.44	4.29	0.02	1.92	0.06	0.36	3.39	0.04	5.64	99.97
12MF03	**18**	71.56	0.79	13.49	4.10	0.02	1.75	0.05	0.27	2.79	0.04	4.94	99.79
7M01	**19**	62.21	0.80	20.96	3.03	0.02	1.54	0.03	0.19	3.48	0.04	7.71	100.00
7M02	**20**	43.17	0.62	16.58	2.07	0.01	1.17	0.22	0.15	3.25	0.35	32.10	99.69
7M03	**21**	61.01	0.87	14.45	8.85	0.08	2.32	0.20	0.14	2.49	0.08	9.56	100.03
12M04	**22**	80.96	0.01	12.50	0.82	0.01	0.11	0.05	0.35	2.44	0.04	2.88	100.15
12MB01	**23**	55.87	0.84	20.88	7.05	0.06	4.33	0.60	1.54	0.13	0.03	2.08	93.40
12MB02	**24**	74.05	0.10	15.07	0.67	0.06	0.24	0.30	2.51	4.88	0.18	1.80	99.86
12MB03	**25**	74.24	0.06	15.26	0.52	0.05	0.20	0.29	2.90	4.10	0.18	1.87	99.67
12MB06	**26**	78.31	0.02	13.85	0.69	0.02	0.20	0.08	0.38	3.51	0.04	2.65	99.75
12MC04	**27**	60.38	0.79	19.15	5.58	0.04	3.89	0.59	1.31	1.01	0.03	1.94	94.72
BB01	**28**	42.24	3.24	11.93	12.01	0.16	12.29	11.40	2.20	0.65	0.72	2.78	99.61
BB02	**29**	26.65	2.89	9.75	7.87	0.36	5.59	23.05	0.99	1.30	1.40	19.18	99.04
BB03	**30**	28.26	3.28	10.97	5.79	0.23	5.27	22.40	1.14	1.34	1.05	19.09	98.82
BB04	**31**	30.77	2.88	10.66	15.30	0.25	10.56	14.20	0.57	1.02	2.83	10.15	99.17

SAMPLE	SCA	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	LOI	SUM
BB05	**32**	36.38	2.94	11.57	14.83	0.21	10.95	10.24	0.76	1.16	1.40	8.97	99.41
BB06	**33**	39.47	3.06	12.91	18.01	0.17	12.06	6.16	1.63	0.61	0.69	4.85	99.62
BB07	**34**	34.80	3.64	12.54	8.24	0.18	8.35	18.10	0.96	0.29	1.07	10.36	98.52
BB08	**35**	24.43	3.64	10.12	7.63	0.26	6.02	23.56	1.00	0.29	0.66	20.97	98.58
BB09	**36**	38.27	2.69	11.18	8.46	0.19	9.49	16.35	1.17	0.90	0.75	10.34	99.77

Values are expressed as weight %, on oven-dried [110°C] basis.

LOI = loss on ignition at 1000°C

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TRACE ELEMENT ANALYSES

SAMPLE	SCA	As	Ba	Ce	Cr	Cu	Ga	La	Nb	Ni	Pb	Rb	Sc	Sr	Th	U	V	Y	Zn	Zr
Sample # 1	**1**	5	302	71	99	1	26	53	22	43	24	457	12	67	19	12	102	18	112	179
Sample # 2	**2**	<1	47	33	102	<1	17	20	23	9	32	16	12	227	14	2	84	20	130	329
Sample # 3	**3**	<1	297	87	79	7	25	51	18	10	27	234	9	149	15	3	85	40	108	212
Sample # 4	**4**	1	175	84	93	<1	26	54	44	12	22	237	4	125	15	4	78	15	105	305
Sample # 5	**5**	12	330	110	156	4	34	55	31	27	28	14	13	272	16	2	158	36	179	122
Sample # 6	**6**	30	301	100	78	123	26	62	33	20	23	950	<2	8	15	3	56	38	42	247
Sample # 7	**7**	4	117	23	90	93	23	13	19	33	139	90	10	109	15	4	104	25	113	147
Sample # 8	**8**	2	60	64	133	16	29	21	20	35	34	24	10	116	20	2	125	34	211	167
Sample # 9	**9**	1	10	103	120	<1	32	56	25	19	42	9	14	221	9	2	121	21	282	109
Sample # 12	**10**	12	55	64	3	2	23	36	21	11	60	533	15	42	12	2	26	39	42	48
Sample # 14	**11**	2	39	34	1	3	23	23	22	1	40	639	2	30	6	5	11	22	22	41

SAMPLE	SCA	As	Ba	Ce	Cr	Cu	Ga	La	Nb	Ni	Pb	Rb	Sc	Sr	Th	U	V	Y	Zn	Zr
Sample # 15	**12**	<1	<5	34	<1	3	30	18	29	<1	26	668	<2	21	2	3	7	15	16	33
Sample # 20	**13**	<1	<5	54	<1	1	29	30	28	2	41	706	<2	18	2	2	11	40	22	33
Sample # 21	**14**	<1	80	37	<1	<1	23	24	25	1	56	806	<2	27	2	2	15	28	59	36
Sample # 23	**15**	1	20	31	<1	1	23	23	27	2	33	809	<2	27	6	2	8	21	34	38
12MF01	**16**	8	381	79	63	14	14	43	19	20	19	115	13	23	11	4	75	48	73	395
12MF02	**17**	10	531	90	100	24	22	56	19	34	30	184	14	25	15	4	113	38	99	225
12MF03	**18**	11	422	77	85	19	19	45	17	26	25	153	16	23	14	5	93	36	65	274
7M01	**19**	1	546	76	94	11	29	40	19	35	37	197	18	49	15	4	112	29	59	201
7M02	**20**	2	725	85	90	22	22	47	13	30	31	182	15	217	15	4	102	30	64	135
7M03	**21**	32	470	73	95	15	21	43	20	63	24	141	13	34	13	3	94	36	106	240
12M04	**22**	3	96	28	1	<1	16	14	11	2	26	125	5	22	4	4	20	28	36	47
12MB01	**23**	65	50	118	144	15	28	59	25	24	35	14	18	225	17	2	143	36	189	152
12MB02	**24**	1	71	31	<1	<1	21	26	18	2	60	587	<2	26	6	3	8	23	20	47
12MB03	**25**	<1	13	20	<1	<1	27	16	23	7	32	546	<2	18	4	2	9	16	21	33
12MB06	**26**	3	138	27	1	<1	20	9	11	2	8	165	3	13	4	5	6	32	14	46
12MC04	**27**	1	203	68	135	1	27	35	17	17	22	91	15	262	19	2	131	20	142	120
BB01	**28**	3	642	104	554	49	18	57	71	370	7	17	29	1006	8	3	246	32	82	268
BB02	**29**	1	781	148	602	53	11	78	76	328	10	33	31	616	8	2	197	40	54	281
BB03	**30**	3	930	143	615	48	15	87	82	291	10	33	35	606	7	<1	248	36	55	311
BB04	**31**	2	639	208	723	33	18	129	61	486	5	27	26	441	6	2	215	61	90	242
BB05	**32**	2	656	142	709	54	18	81	57	386	5	30	28	306	5	2	226	44	99	247

SAMPLE	SC A	As	Ba	Ce	Cr	Cu	Ga	La	Nb	Ni	Pb	Rb	Sc	Sr	Th	U	V	Y	Zn	Zr
BB06	**33**	1	418	117	799	41	22	62	70	485	7	8	28	330	8	<1	218	33	108	285
BB07	**34**	5	4895	68	608	53	15	50	70	295	2	7	31	964	5	1	266	32	79	286
BB08	**35**	19	407	91	768	68	14	49	69	305	13	9	41	386	6	<1	213	34	65	305
BB09	**36**	<1	592	98	691	41	16	61	65	489	8	21	21	702	7	2	212	33	85	251

Values are expressed as mg/kg, on oven-dried [110°C] basis.